Development of a Metal Cutting

W-Beam Guardrail Terminal

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STATEMENT OF CONFIDENTIALITY

This report contains proprietary information and is intended to be viewed only by authorized persons for the purpose of obtaining approval from the Federal Highway Administration for use of this system on public roads. This information will be available to the public after the patent application has been filed.

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1 INTRODUCTION

Highway engineers have been searching for years for a safe and economical means of terminating strong post W-beam systems. Up until now there have only been a handful of approved W-beam end treatments, and serious questions have been raised lately about the safety of a number of these systems. In response to these concerns, a study was undertaken to develop an economical energy absorbing guardrail terminal. The objective of the study was to develop a terminal which could be installed tangent to the roadway and that would meet the safety criteria set forth in NCHRP 230 (1).

2 SYSTEM DETAILS

The energy absorbing guardrail terminal developed in this study consists of an impact head mounted on the end of a standard wood post W-beam system. The concept behind this system is that when the impact head is struck by a vehicle, three cutter teeth within the head cut the W-beam along the peaks and valley. The W-beam is cut into four relatively flat plates that are then bent out of the path of the impacting vehicle.

Photographs of the system are shown in Figures 1 and 2, and a sketch of this system is shown in Figure 3. Details of the impact head are shown in Figures 4 and 5. These cutting teeth are fabricated from AR250 abrasion resistant steel, and their dimensions are shown in Figure 6. The end of the W-beam is notched as shown in Figure 7 and the cutters are placed inside these notches to ensure that they start cutting in the correct location. The cutting action produces a force which brings the vehicle to a controlled stop in which the occupant ridedown decelerations and impact velocities are within the range required by NCHRP 230 (1). Post Nos. 1 and 2 had 2 3/8 in. diameter holes parallel to the rail near the groundline, and post Nos. 3,4,5, and 6 were standard 6" x 8" CRT posts with 3 1/2 in. diameter holes at the groundline and 16 in. below. These holes weaken the posts for end on impacts, but allow the posts to retain most of their strength in the direction perpendicular to the rail.

In addition to head-on impacts, the guardrail terminal must also be capable of redirecting a 4500 lb sedan at the beginning of the length of need at 60 mph and 25 degrees. With this condition in mind, the standard breakaway cable anchor system was modified so that the connection from the cable to the W-beam would develop the tensile force necessary for redirection of a vehicle, but would release during an end on impact. This was accomplished by cutting tabs in the W-beam, then bending them out to fit in slots of a cable anchor box. Photos of this anchoring system are shown in Figure 8 and the final design is shown in Figures 9 and 10.

In the event of a redirectional type impact downstream of the terminal, tensile forces in the rail are transferred through the anchor cable and into the first post and foundation tube. In order to distribute this load between the first and second posts, a strut was installed between the first and second posts to distribute the cable anchor loads between these posts. The location of this strut can be seen in Figure 3 and details are shown in Figure 11. The system was tested with a strut measuring 66.5 in. long in conjunction with shims placed between the yoke and the post. In order to simplify the design, the length of the ground struts should be increased to 68.25 in., so that shims are not required, as shown in Figure 11. Note that the distance between the end of the impact head's feeder shute and the first post is somewhat limited. When the first two posts are spaced on 6-ft 3-in. centers, the distance between the end of the shute and the cable anchor box is only 10.5 in., and the distance between the anchor box and the second post is only 4.5 in. The impact head must break the first post and release the cable anchor before the feeder shute reaches the anchor box and the anchor box must be fully disengaged before reaching the second post. Therefore it is important to maintain the distance between the impact head's cable anchor box and the second post.

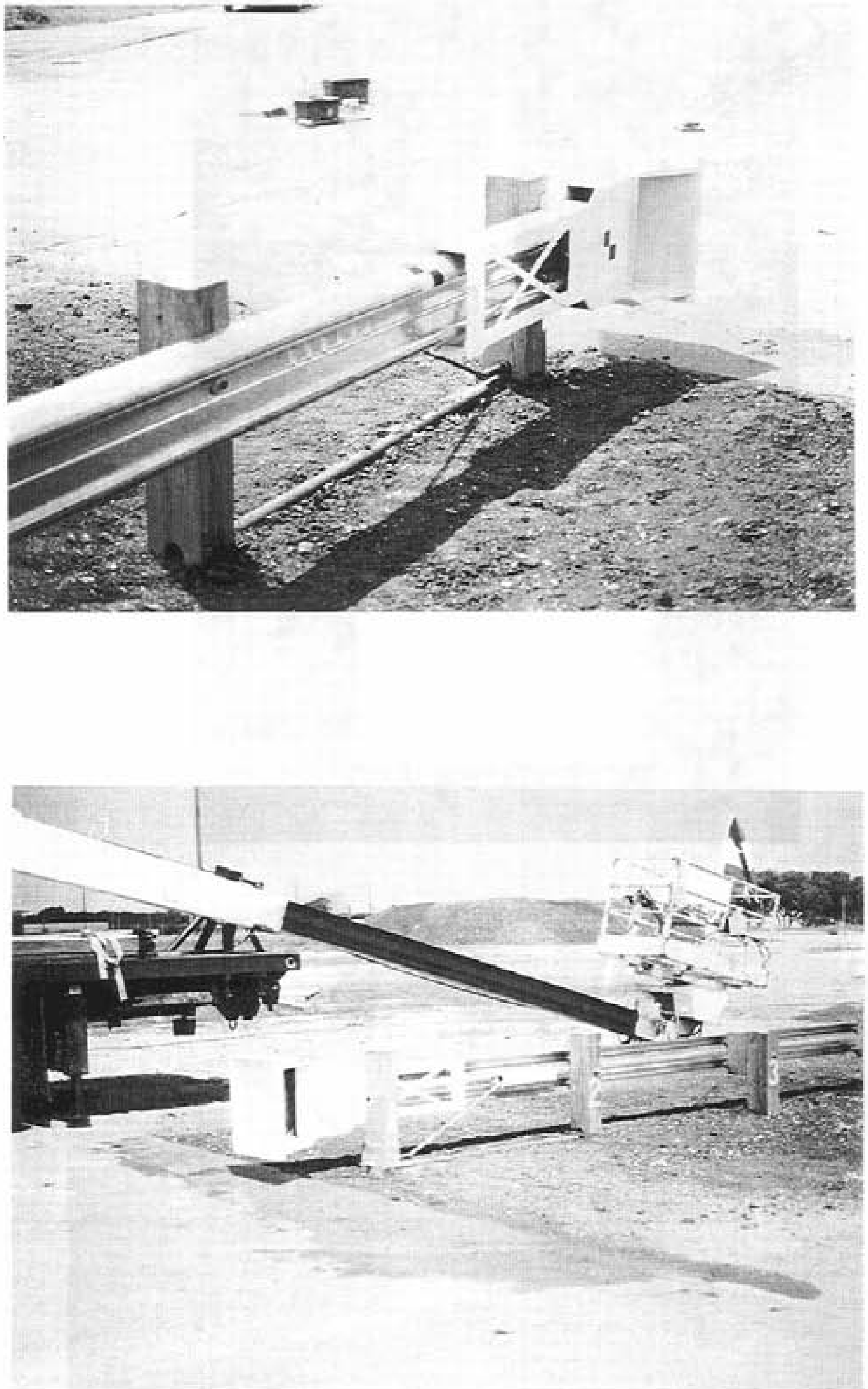
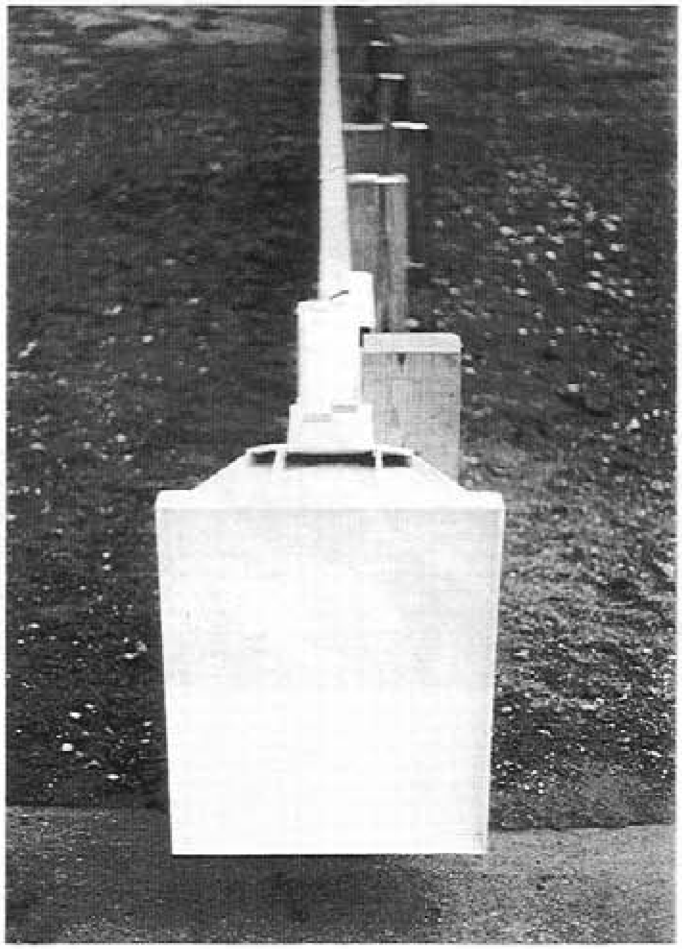


Figure 1. Photographs of Metal Cutting Terminal



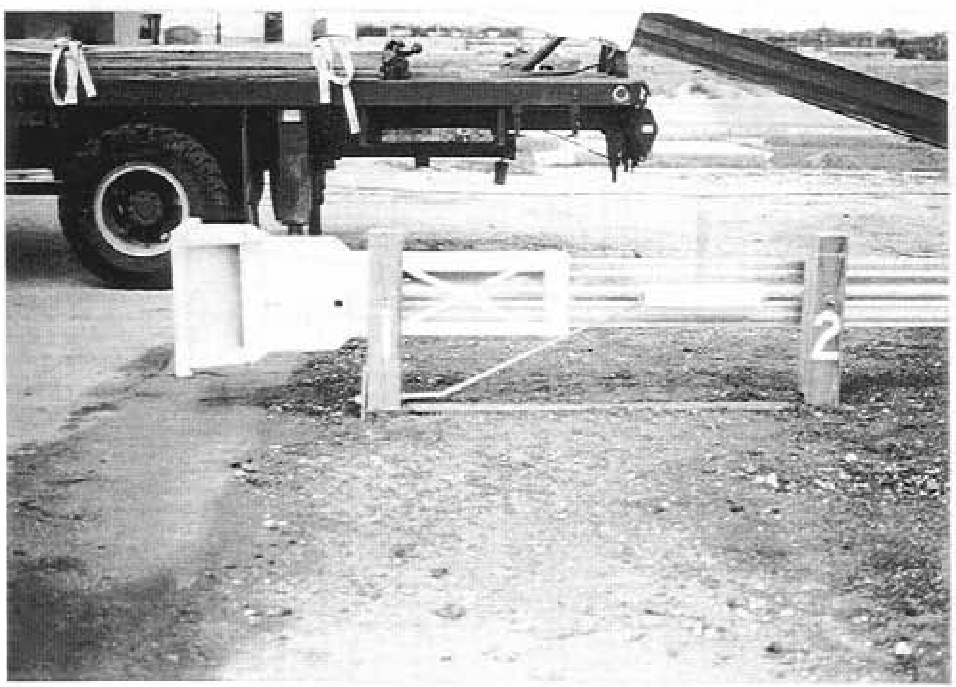
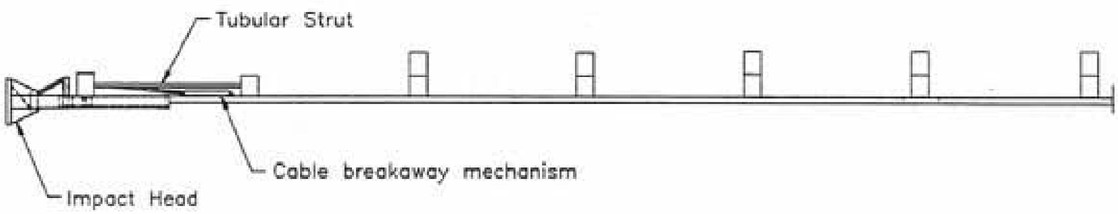


Figure 2. Photographs of Metal Cutting Terminal (continued)



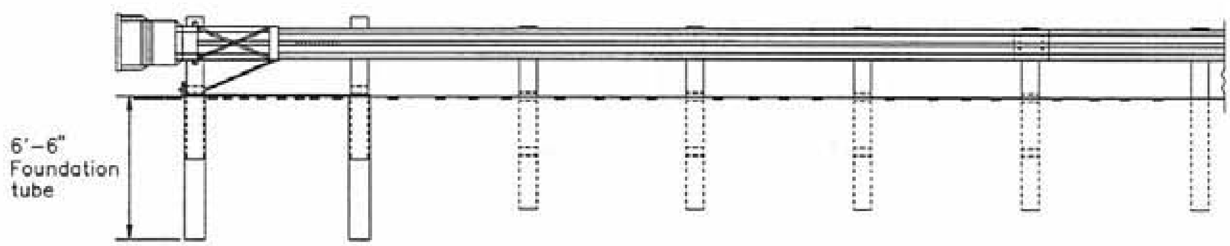


Figure 3. Metal Cutting W-beam Guardrail Terminal

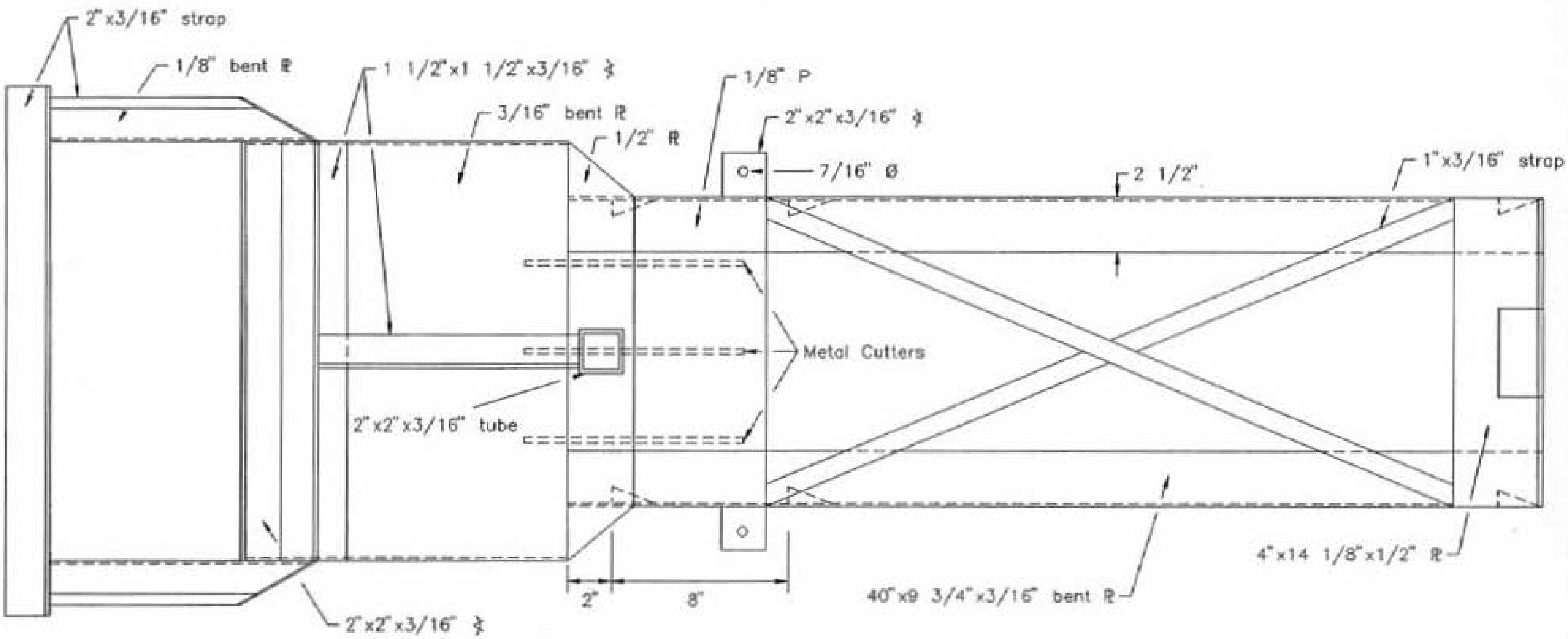


Figure 4. Side View of Metal Cutting Impact Head

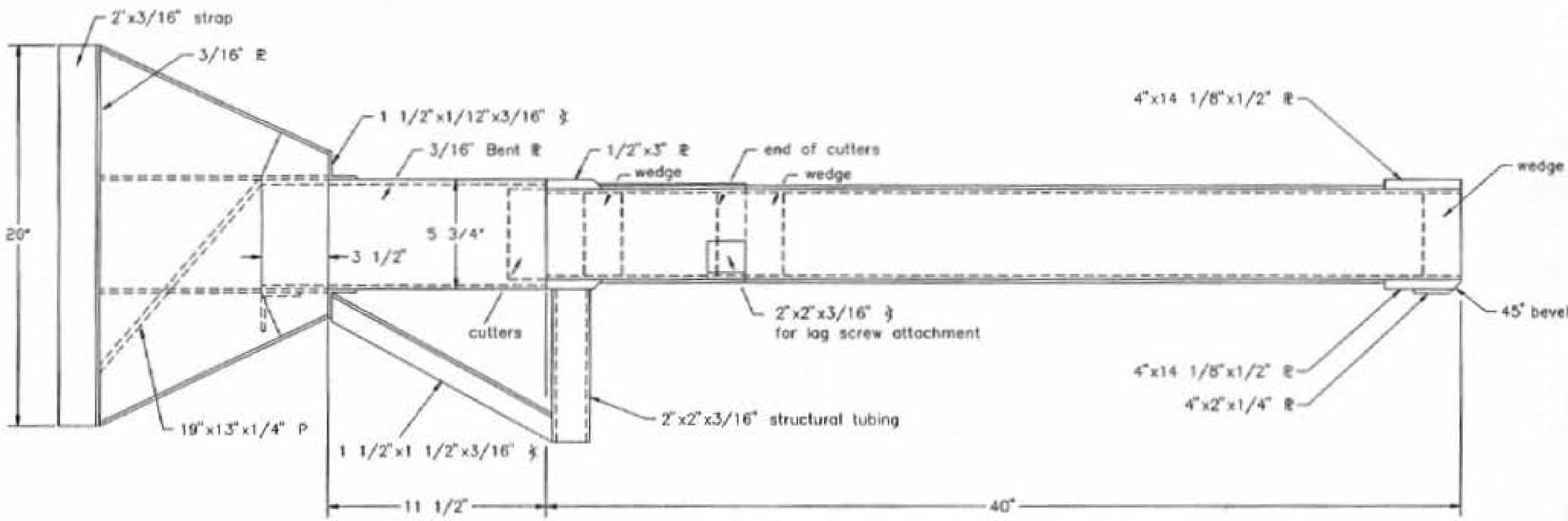


Figure 5. Top View of Metal Cutting Impact Head

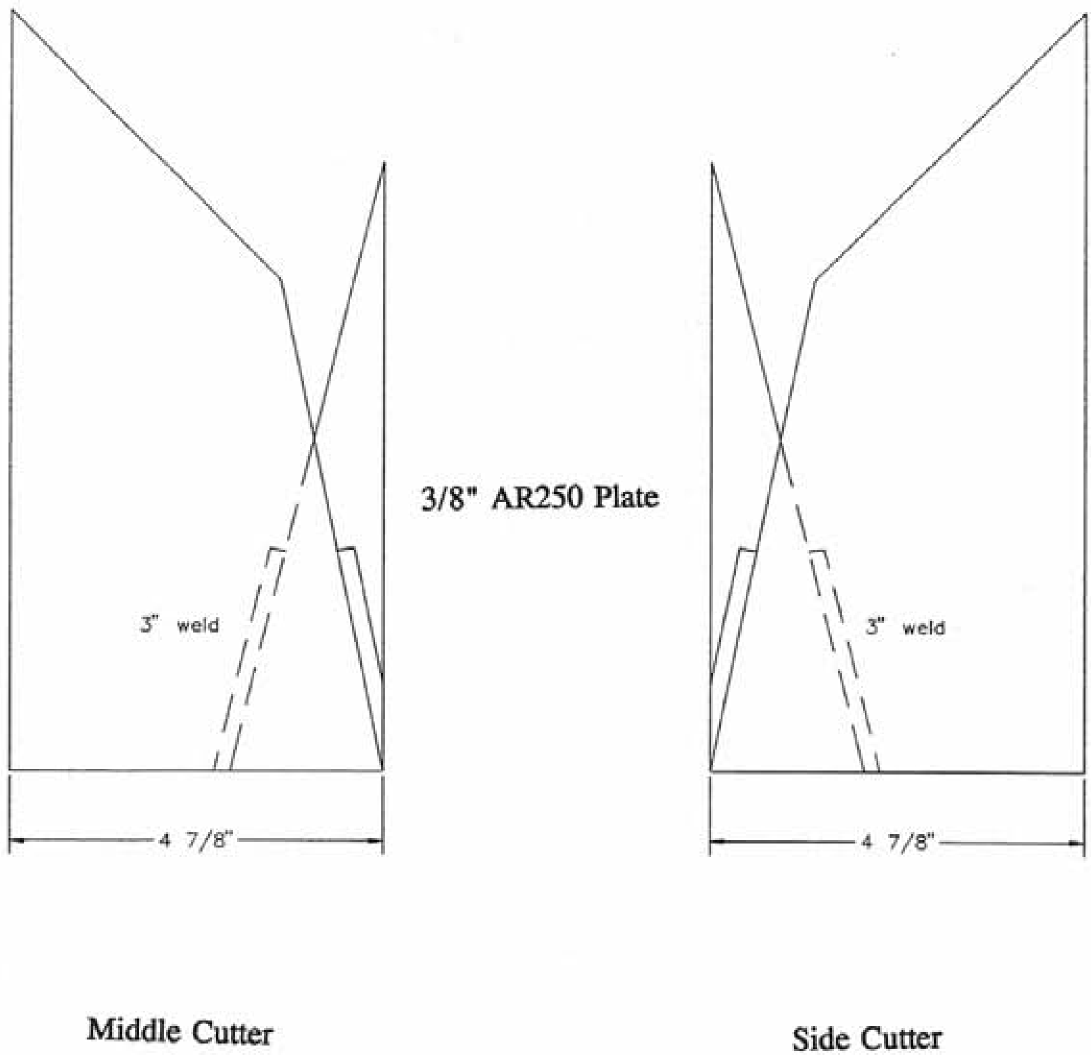


Figure 6. Details of Metal Cutting Teeth

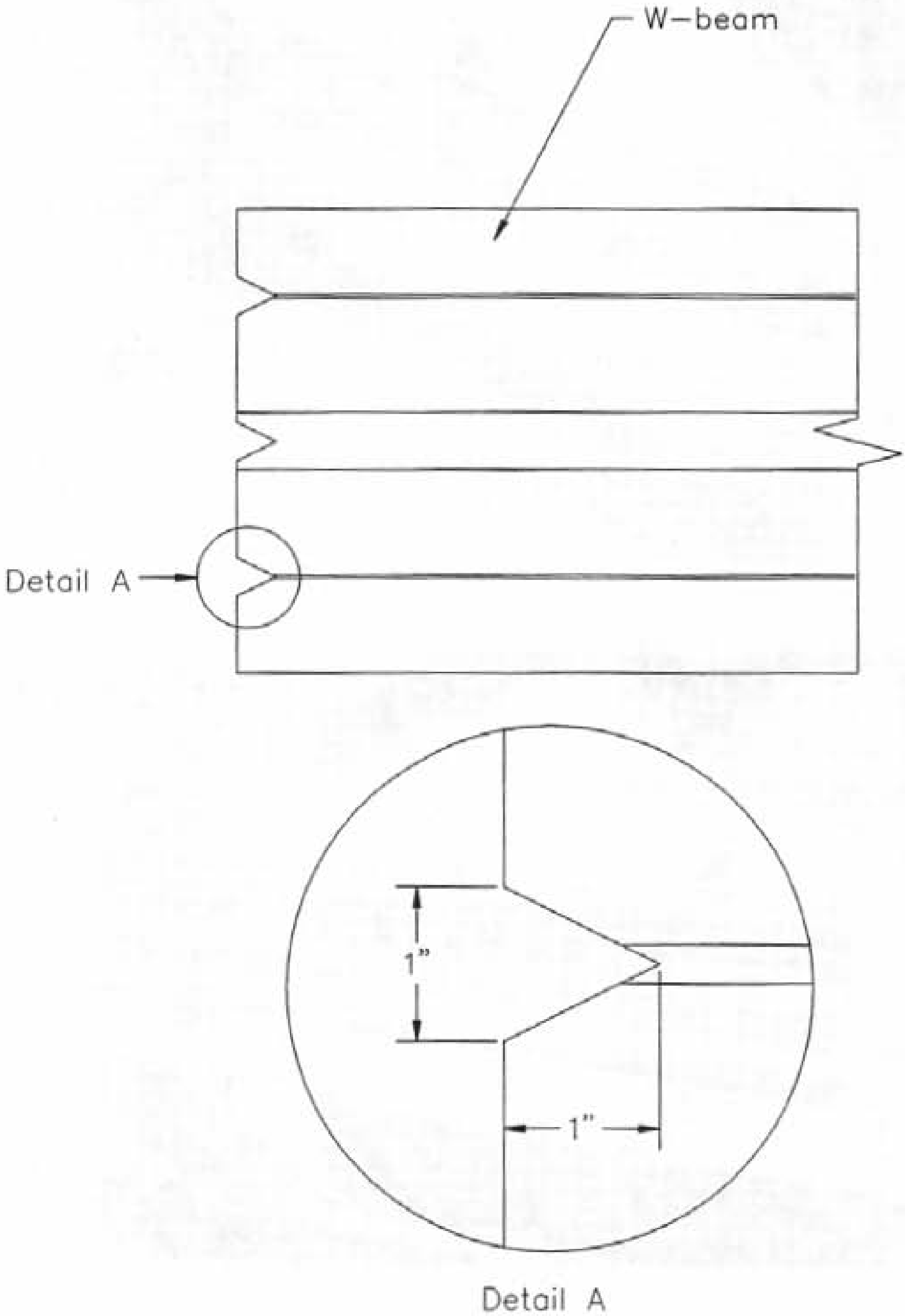


Figure 7. Details of W-beam Notches

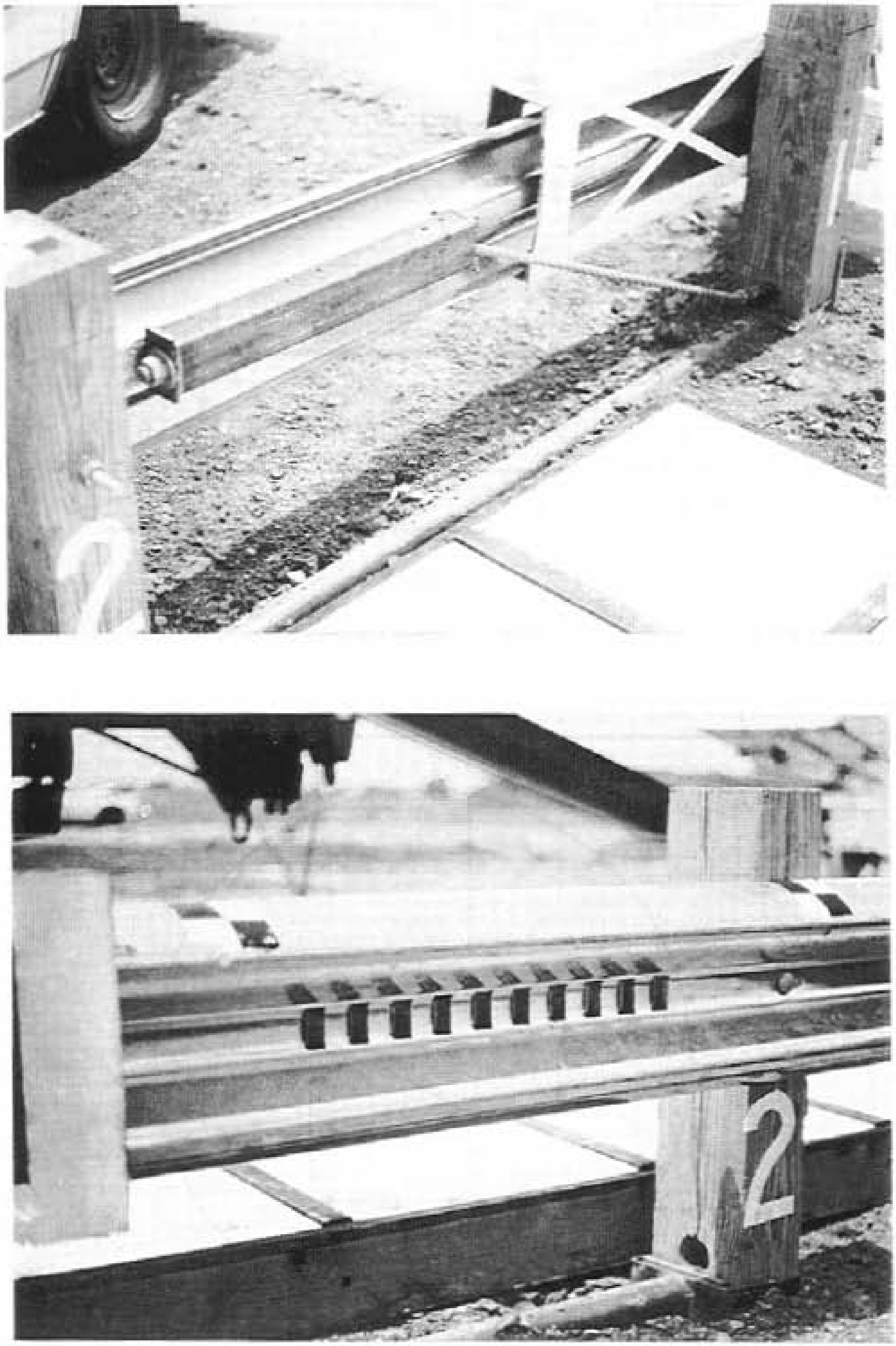


Figure 8. Photographs of Cable Anchor System

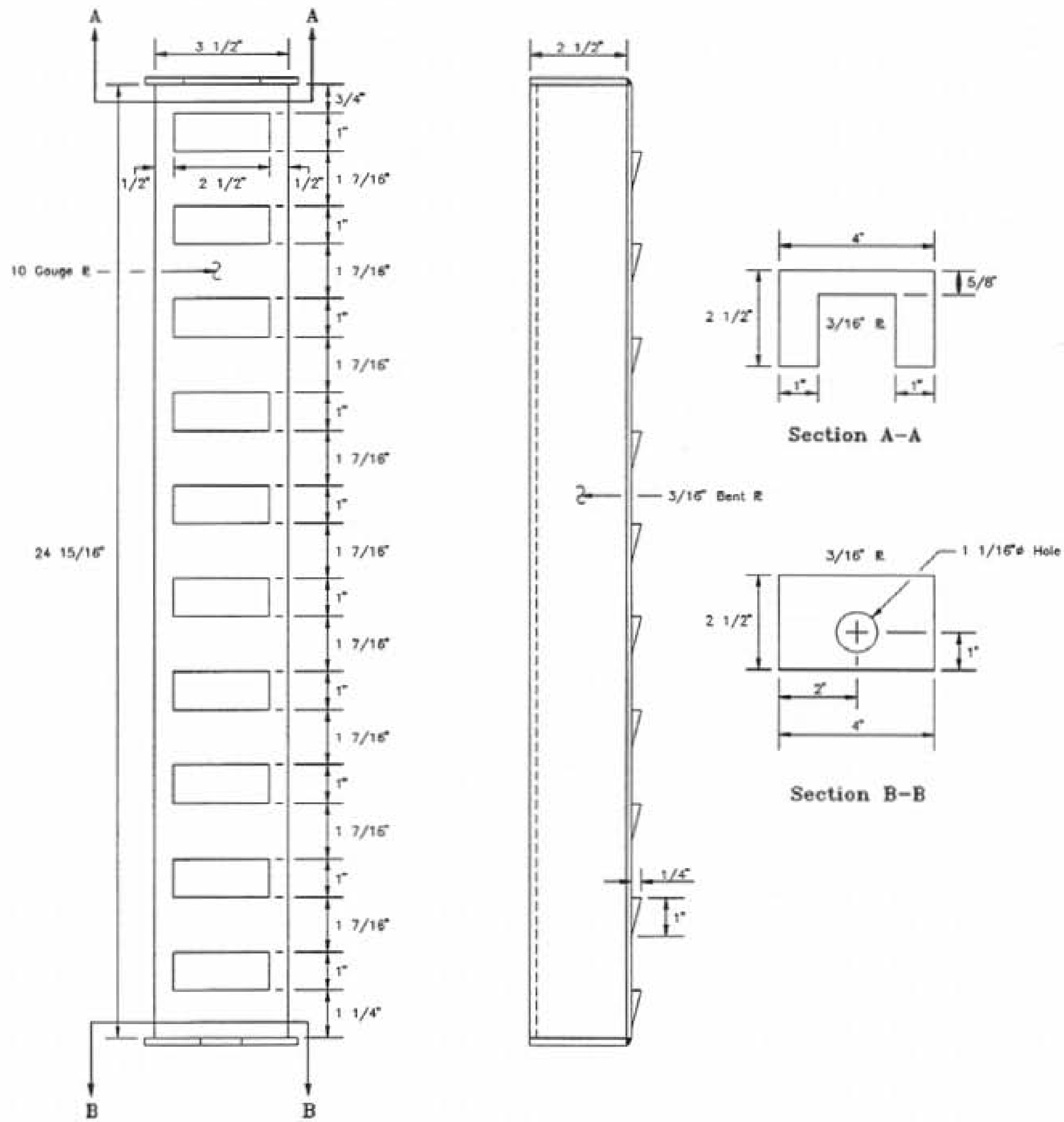


Figure 9. Breakaway Cable Anchor Box Details

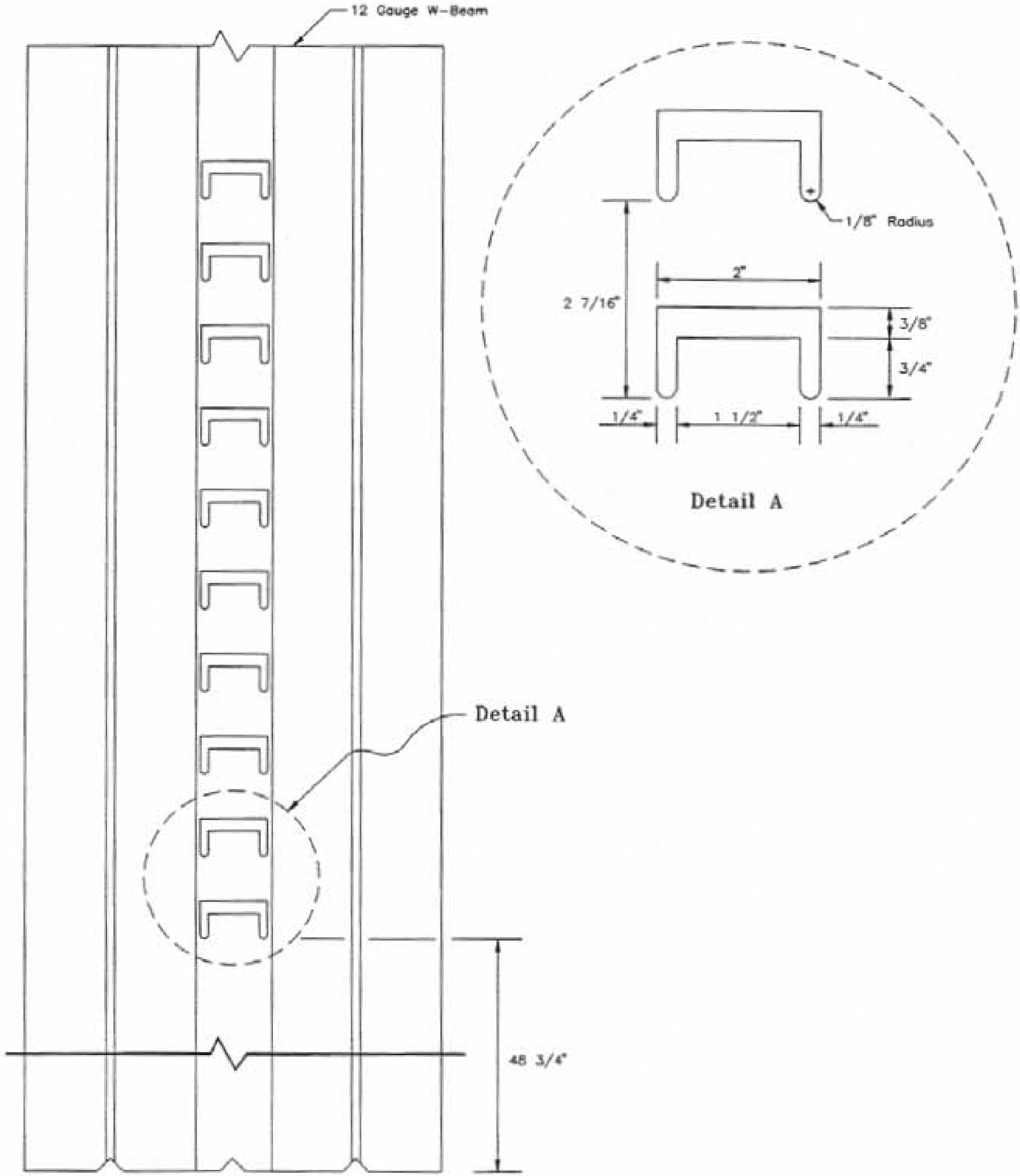


Figure 10. Breakaway Cable Anchor W-beam Attachment Details

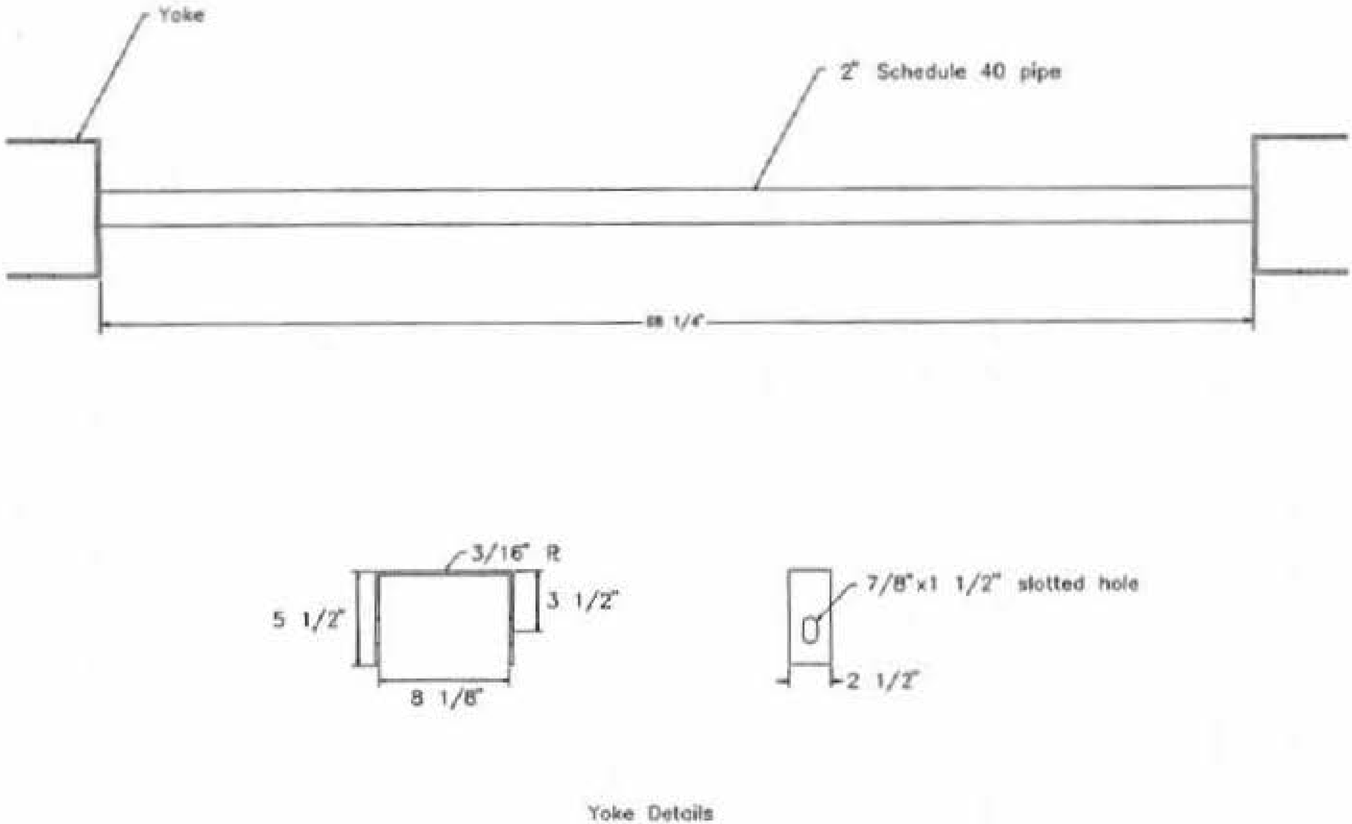


Figure 11. End Strut Details

3 TEST CONDITIONS

3.1 Test Vehicles

Two 1988 Ford Festivas were used in Tests MCS-1 and MCS-2. A 1988 Yugo was used as a test vehicle in Test MCS-3. Four 1986 Ford LTDs were used in tests MCS-4, MCS-5, MCS-6, and MCS-7. Photographs of the test vehicles used in the successful compliance tests are shown in Figures 12, 14, and 16, and data sheets for each vehicle are shown in Figures 13, 15, and 17.

Black and white-checkered targets were placed on the test vehicles for high-speed film analysis. Two targets were located on the center of gravity, one on the top and one on the side of the test vehicle. Additional targets were located for reference so that they could be viewed from all cameras. The front wheels of the test vehicle were aligned for camber, caster, and toe-in values of zero so that the vehicle would track properly along the guide cable. Two 5B flash bulbs, fired by a pressure tape switch on the front bumper, were mounted on the roof of the vehicle to establish the time of impact.

3.2 Data Acquisition Systems

3.2.1 Accelerometers

An Environmental Data Recorder (EDR-3) is used to record the accelerations during the full-scale vehicle compliance tests. This is a self contained unit which consists of a triaxial accelerometer system which triggers upon impact, and records and stores the data on board. DynaMax software is then used to download the EDR-3 unit, filter the data, and convert it to an ASCII file. "DSP" software is then used to analyze and plot the data.

3.2.2 High Speed Photography

Three to five high-speed 16-mm cameras, with operating speeds of approximately 500 frames/sec, were used to film each crash test. The film was analyzed using a Vanguard Motion Analyzer. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed film.

3.2.3 Speed Trap

Six pressure tape switches spaced at 5-ft intervals were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light and sent an electronic timing mark to the data acquisition system as the front tire of the test vehicle passed over it. Test vehicle speeds were determined from electronic timing mark data recorded on "Computerscope" software. Strobe lights and high speed film analysis are used only as a backup in the event that vehicle speeds cannot be determined from the electronic data.

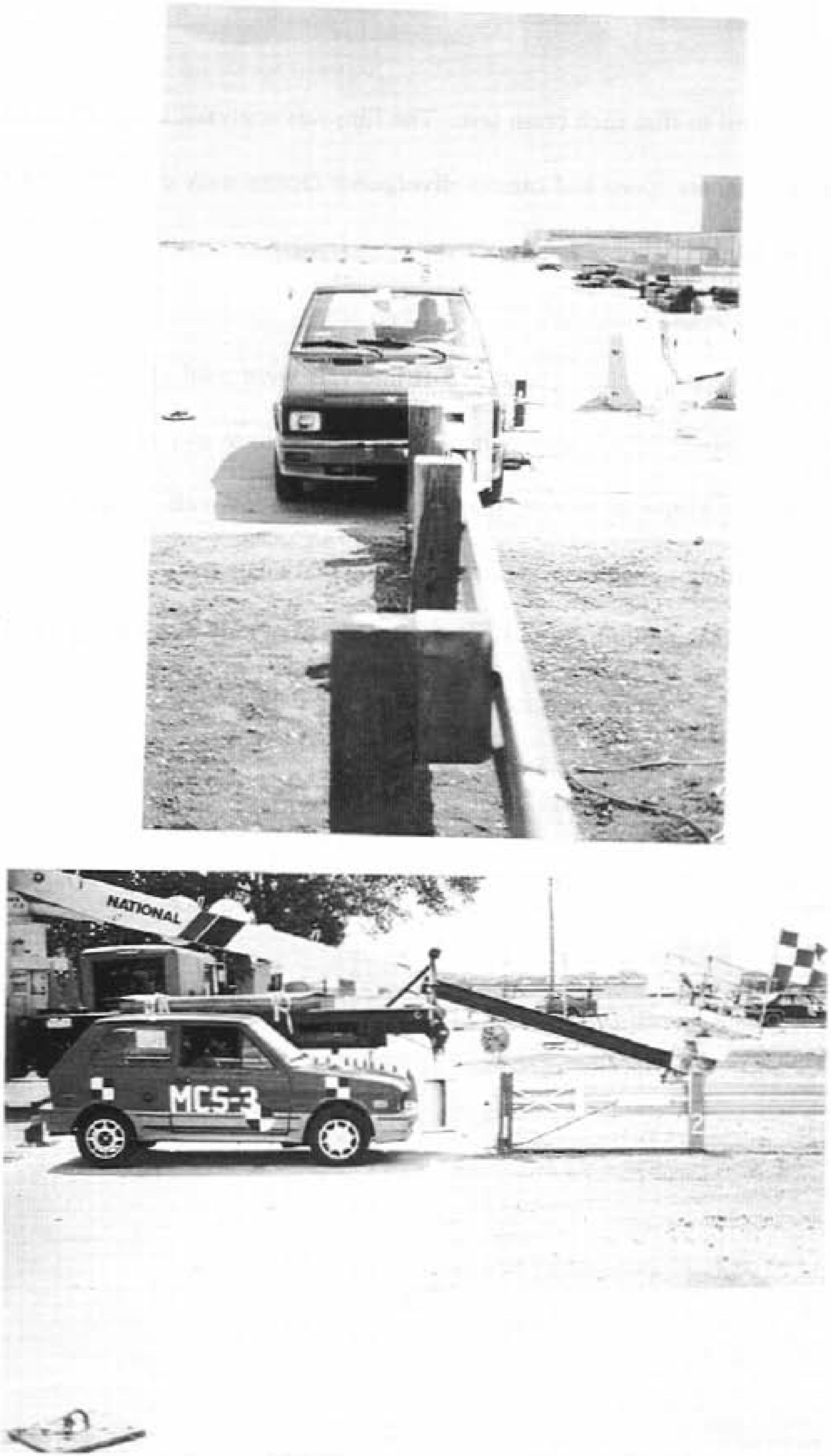


Figure 12. Test Vehicle Photographs, Test MCS-3

Make: Yugo

Test No.: MCS-3

Model: GVX

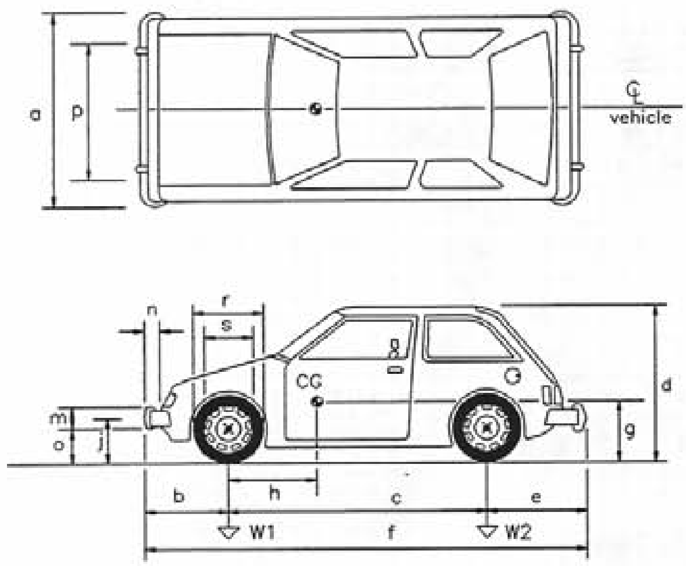
Tire Size: P155/80R13

Year: 1988

V.I.N. #: VX1BC1512JK430661

Vehicle Geometry
Inches

a —	61.0	b —	29.0
c —	85.0	d —	56.0
e —	25.5	f —	139.5
g —	19.0	h —	28.0
j —	17.3	m —	5.5
n —	5.5	o —	14.5
p —	52.0	r —	22.5
s —	14.5		



Engine Size: 4 cyl.

Transmission: manual

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	1240	1202	1285
W2	620	622	704
Wtotal	1860	1824	1989

Damage prior to test: NONE

Conversion Factors: 1in.=2.54cm. 1lb.=0.454kg.

Figure 13. Test Vehicle Data Sheet, Test MCS-3

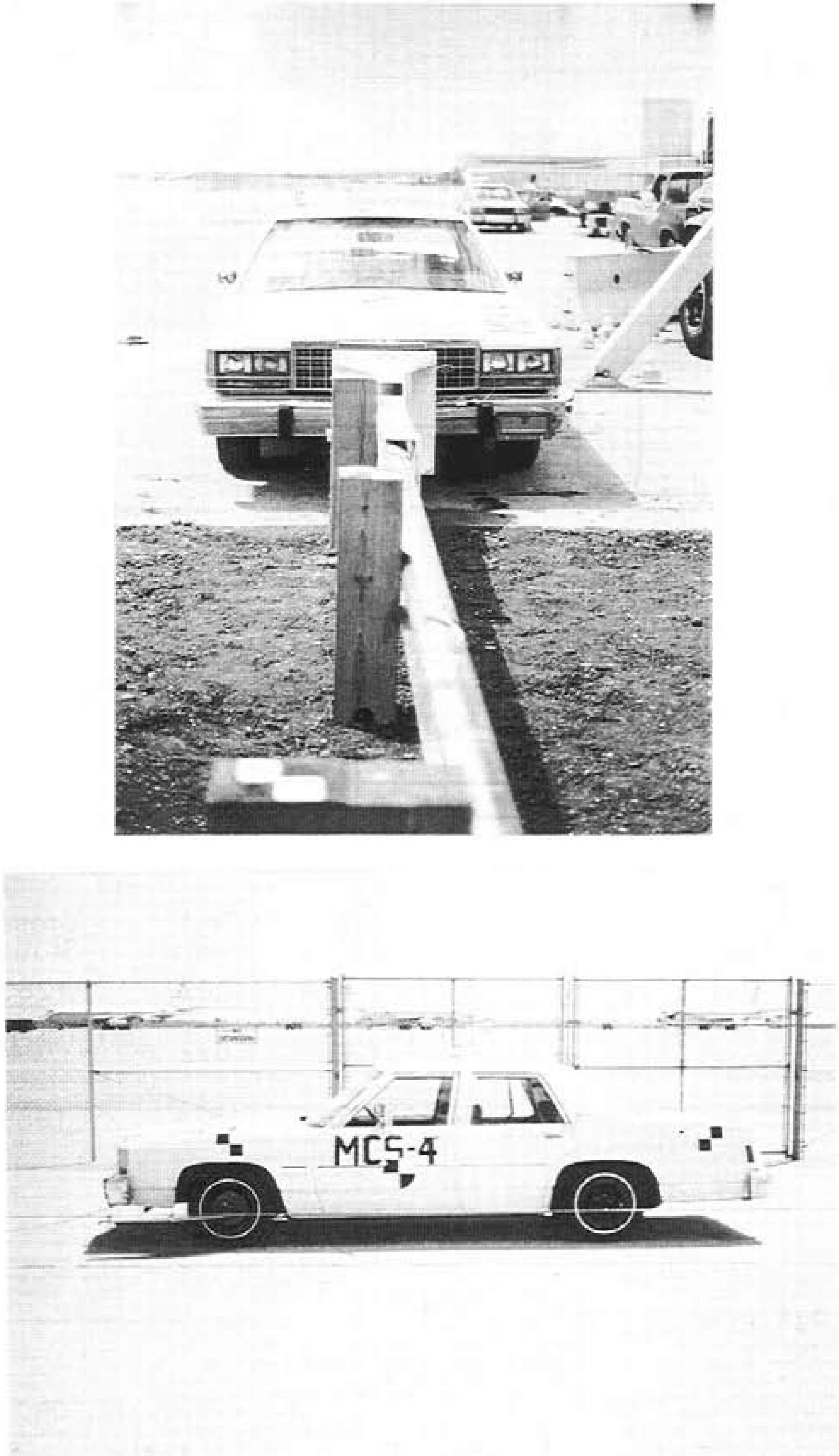


Figure 14. Test Vehicle Photographs, Test MCS-4

Make: Ford (White)

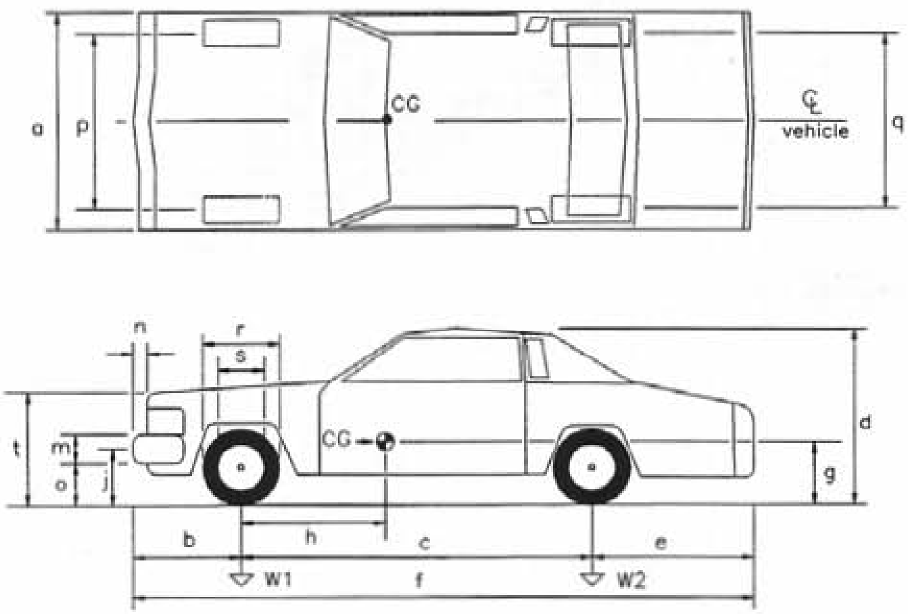
Test No.: MCS-4

Model: LTD Crown Victoria

Tire Size: P225/70-R15

Year: 1986

VIN: 2FABP43G1GX181602



Vehicle Geometry
Inches

a —	73.0	b —	39.0
c —	114.0	d —	56.0
e —	52.5	f —	214.0
g —	22.5	h —	51.0
j —	17.0	m —	7.0
n —	4.0	o —	13.5
p —	62.5	q —	62.0
r —	26.0	s —	15.0
t —	33.5		

Engine Size: 351 in^3

Transmission: automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	2300	2489	2489
W2	1660	2014	2014
Wtotal	3960	4503	4503

Damage prior to test: NONE

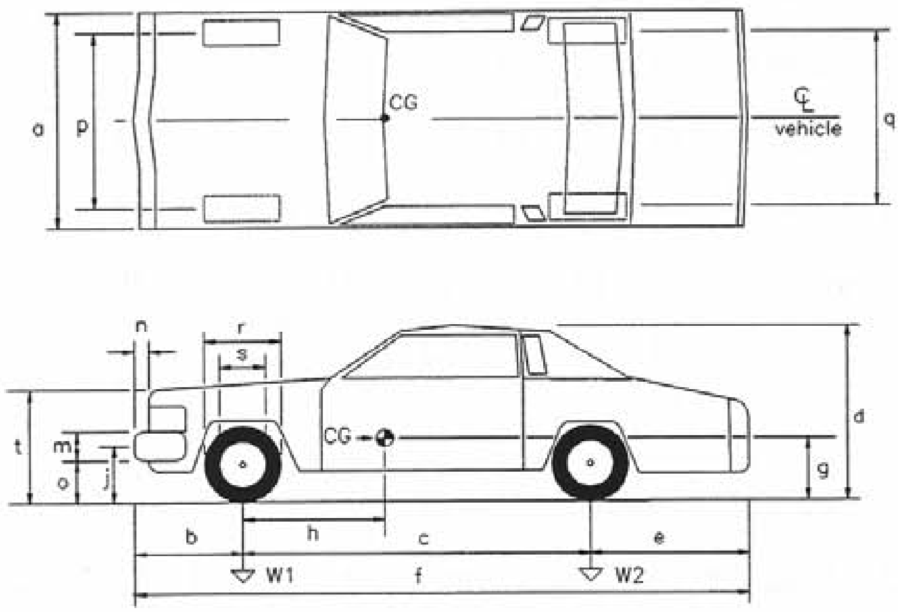
Figure 15. Test Vehicle Data Sheet, Test MCS-4

Figure 16. Test Vehicle Photographs, Test MCS-7

Make: Ford (White) Test No.: MCS-7

Model: LTD Crown Victoria Tire Size: P225/70-R15

Year: 1986 VIN: 2FABP43G4GX181576



Vehicle Geometry
Inches

a —	73.0	b —	39.0
c —	114.0	d —	56.0
e —	52.5	f —	214.0
g —	22.5	h —	51.0
j —	17.0	m —	7.0
n —	4.0	o —	13.5
p —	62.5	q —	62.0
r —	26.0	s —	15.0
t —	33.5		

Engine Size: 351 in^3

Transmission: automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	2250	2484	2484
W2	1460	2028	2028
Wtotal	3710	4512	4512

Damage prior to test: NONE

Figure 17. Test Vehicle Data Sheet, Test MCS-7

4 TEST RESULTS

4.1 Test MCS-1 (1800 lbs, 60 mph, 0 deg.)

In Test MCS-1, the 1988 Ford Festiva impacted the terminal head-on and offset 15 in. to the back side of the guardrail. In this test the guide shute on the impact head was not strong enough. The shute bent after the head had cut through several feet of guardrail, causing the cutter teeth to jam, and impart excessive forces to the vehicle.

After this test several modifications were made to the impact head. The shute was strengthened by increasing the size of the members and adding a truss system to each side. In addition to this, the ends of the cutter teeth were extended to prevent any snagging on the W-beam. A 4 in. post breaker was also added to aid in breaking the first two posts.

4.2 Test MCS-2 (1800 lbs, 60 mph, 0 deg.)

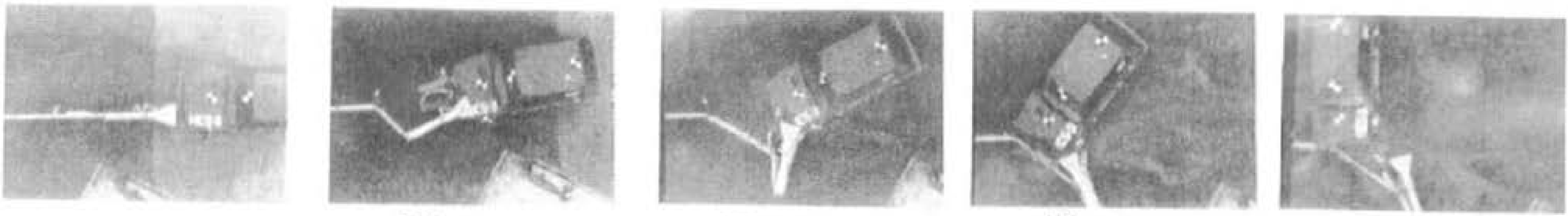
In Test MCS-2, the 1988 Ford Festiva impacted the terminal head-on and offset 15 in. to the back side of the guardrail. In this test the first post did not fracture correctly, as the 4 in. post breaker split the 5.5 in. by 7.5 in. post instead of fracturing it at the groundline. Therefore the cable anchor was not released from the post, and a downward force was imparted into the end of the shute when it reached the cable attachment to the W-beam. The cable attachment did release at this point, but the downward motion of the head had already started, and the W-beam buckled almost immediately. The post breaker was extended to 8 in. for the next test so that the first post would break cleanly at the ground level and eliminate the problem encountered during this test.

4.3 Test MCS-3 (1800 lbs, 60 mph, 0 deg)

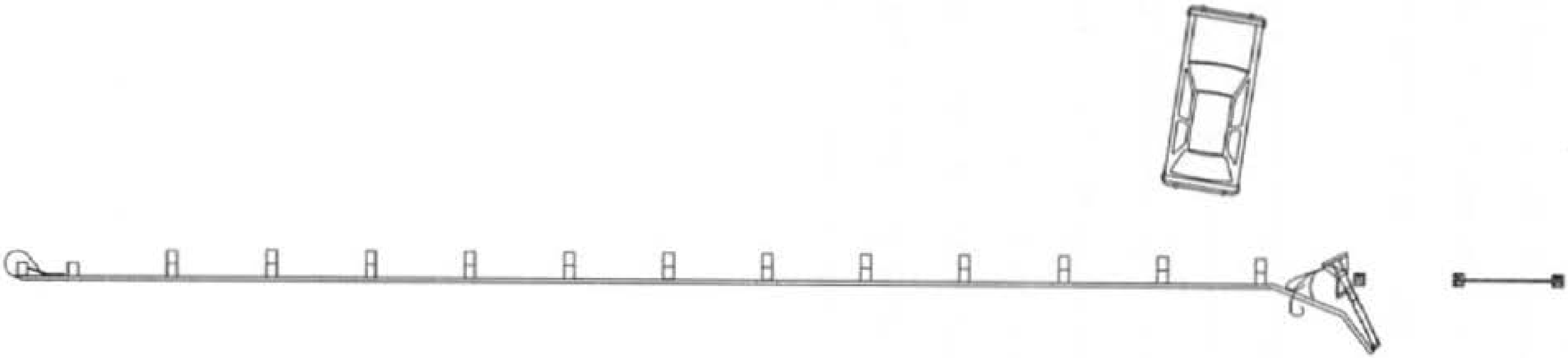
In Test MCS-3, a 1988 Yugo impacted the terminal head-on and offset 15 in. toward the back of the rail at a speed of 63.0 mph. In this test the first post broke cleanly at ground level, and the cable anchor mechanism released as designed. The impact head broke the first two posts and cut through 6' - 6" of W-beam before the vehicle began to yaw out toward the back side of the rail. The vehicle came to rest as shown in Figure 18 with relatively modest damage and no occupant compartment deformation.

The analysis of the accelerometer data showed that the system passed the occupant risk criteria presented by NCHRP 230 (1). The normalized longitudinal occupant impact velocity was 33.3 fps, which is above the design value of 30 fps, but well below the maximum allowable limit of 40 fps. The maximum ridedown acceleration of 17.3 g's was above the design value of 15 g's but below the maximum allowable limit of 20 g's.

A summary of the test results is shown in Figure 18. The damage to the test vehicle is shown in Figure 19 and damage to the installation is shown in Figure 20. Plots of the accelerometer data from Test MCS-3 can be found in Appendix A. A summary of the safety performance results is given in Table 1.



Impact | 150 msec | 300 msec | 450 msec | 600 msec



Test Number	MCS-3
Date	6/16/94
Installation	Metal Cutter Guardrail End Terminal
Length of Installation	100 ft.
Vehicle Model	1988 Yugo
Vehicle Weight	
Curb	1860 lbs
Test Inertial	1824 lbs
Gross Static	1989 lbs
Vehicle Impact Speed	63.0 mph
Vehicle Impact Angle	0 deg

Vehicle Impact Location	15 in. offset to back of rail
Occupant Impact Velocity	
Longitudinal	33.3 fps
Lateral	None
Occupant Ridedown Accelerations	
Longitudinal	17.3 g
Lateral	None
Vehicle Damage Classification	
TAD	12-FC-5
VDI	12FDEN2
Length of Rail Fed through cutter	6 ft. - 6 in.

Figure 18. Summary of Test MCS-3

Figure 19. Test vehicle damage, Test MCS-3

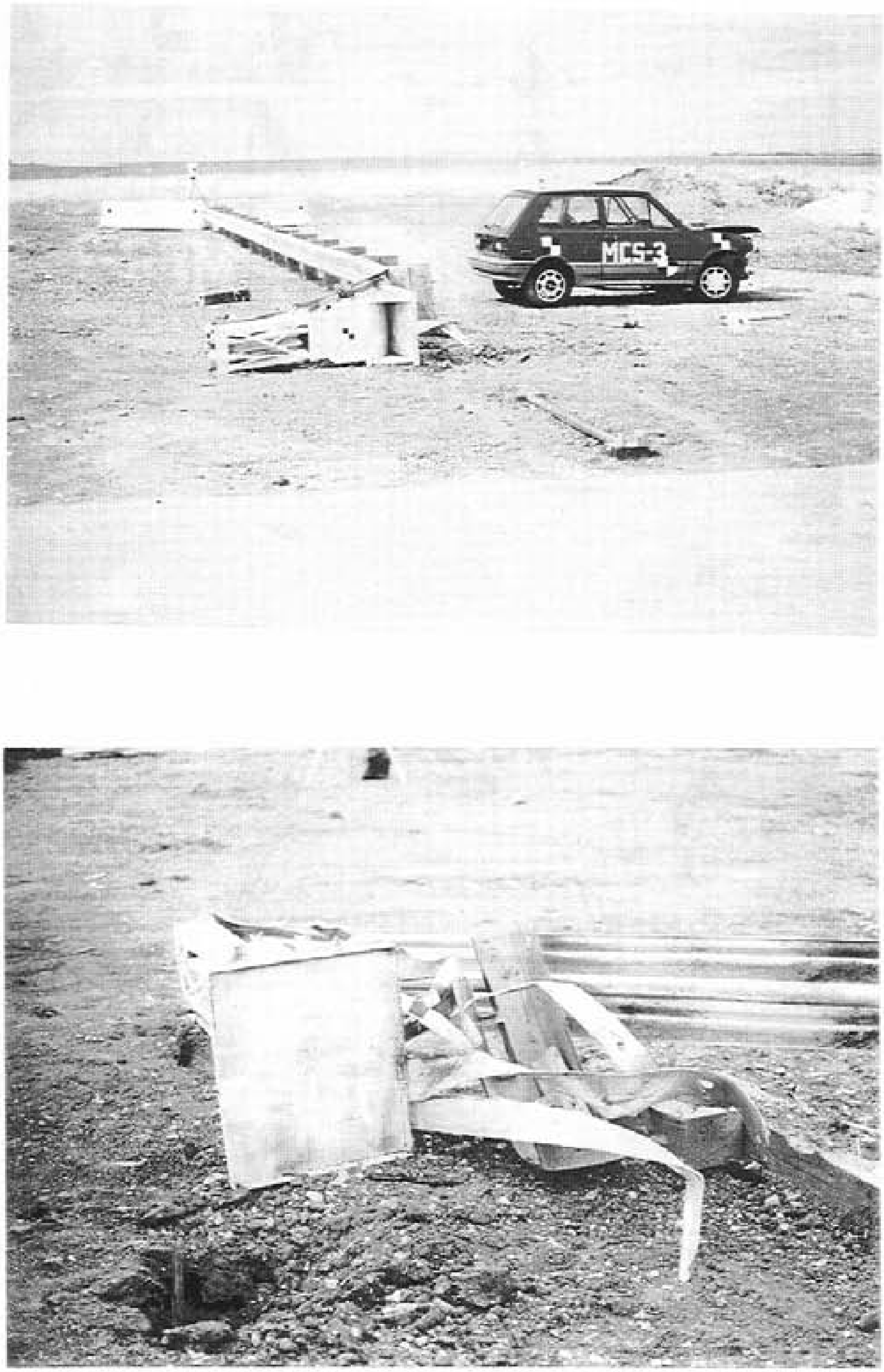


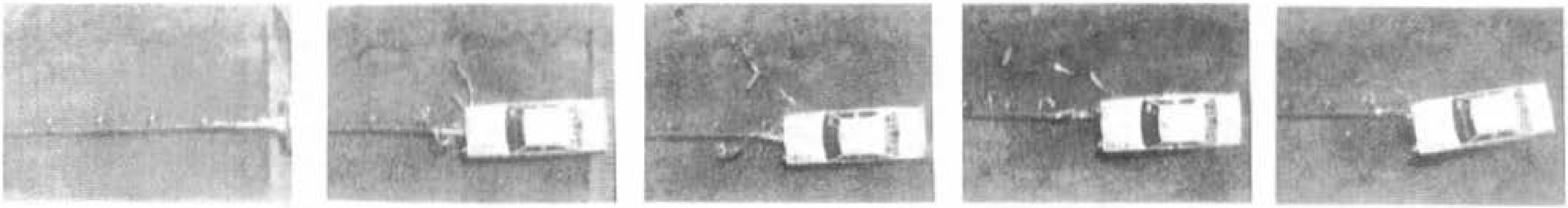
Figure 20. Installation damage, Test MCS-3

4.4 Test MCS-4 (4500 lbs, 60 mph, 0 deg)

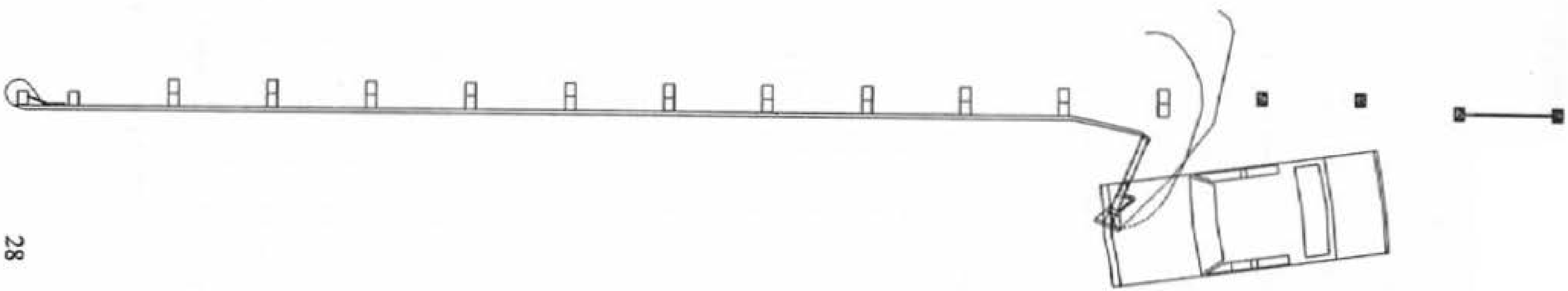
In Test MCS-4, a 1986 Ford LTD impacted the terminal centered and head-on at a speed of 61.6 mph. The impact head cut through 23' - 0" of W-beam before bringing the vehicle to a stop. After the first 4 ft. of cutting, the W-beam was forced down below the top cutting blade and was cut along two surfaces. The metal cutting proceeded to slow the vehicle until the vehicle reached the fourth post. At this time, the vehicle was traveling approximately 10 mph and the low impact speed caused the fourth post to rotate in the soil without breaking. The rotated post formed a ramp which caused the front of the vehicle to be lifted into the air and become disengaged from the metal cutter. However, the vehicle was brought to a controlled stop with no significant risk of vehicle rollover.

Note that the guardrail becoming disengaged from one of the metal cutters was somewhat expected since bogie testing of the metal cutting head exhibited similar behavior. The 15 small car and bogie vehicle tests however all involved the head cutting no less than 7 ft of the guardrail prior to one of the cutters becoming disengaged. When one of the cutters become disengaged, the deceleration forces are shown to increase modestly, approximately 25 percent. Therefore, since the cutter head may not slip off in all cases, we believe that it is important to provide more than 23 ft of unrestrained guardrail in front of the impact head. Therefore the first segment of the W-beam in the final design configuration needs to be approximately 31 ft - 3 in. long.

The analysis of the accelerometer data showed that the performance of the terminal passed the occupant risk criteria presented by NCHRP 230 (1). The normalized longitudinal occupant impact velocity was 23.8 fps, well below the design limit of 30 fps. The maximum ridedown acceleration of 9.2 g's was well below the design limit of 15 g's.



Impact | 236 msec | 472 msec | 708 msec | 944 msec



Test Number	MCS-4
Date	6/22/94
Installation	Metal Cutter Guardrail End Terminal
Length of Installation	100 ft.
Vehicle Model	1986 Ford LTD
Vehicle Weight	
Curb	3960 lbs
Test Inertial	4502 lbs
Gross Static	4502 lbs
Vehicle Impact Speed	61.6 mph
Vehicle Impact Angle	0 deg

Vehicle Impact Location	Center of bumper
Occupant Impact Velocity	
Longitudinal	23.8 fps
Lateral	None
Occupant Ridedown Accelerations	
Longitudinal	9.2 g's
Lateral	None
Vehicle Damage Classification	
TAD	12-FC-5
VDI	12FCEN2
Length of Rail Fed through cutter	23 ft. - 0 in.

Figure 21. Summary of Test MCS-4

Figure 22. Test vehicle damage, Test MCS-4

Figure 23. Installation damage, Test MCS-4

A summary of the test results is shown in Figure 21. The damage to the test vehicle is shown in Figure 22, and damage to the test installation is shown in Figure 23. Plots of the accelerometer data from Test MCS-4 can be found in Appendix A. A summary of the safety performance results is given in Table 1.

4.5 Test MCS-5 (4500 lb, 60 mph, 25 deg)

Test MCS-5 was performed to test the redirectional capacity of the end treatment. A 1986 Ford LTD was directed into the system at 60 mph and 25 degrees. The impact location was at the third post from the upstream end of the system.

For this test, the critical component is the cable anchor mechanism. This mechanism must be capable of developing enough load to redirect the vehicle. The breakaway cable anchor attachment used in this test was similar to the final design shown in Figures 9 and 10 except that it had 6 tabs and the face of the anchor box with the slots was flat. During static testing of this component, the face of the box with the slots deformed, causing an interlock between the tabs in the W-beam and the slots in the box which provided sufficient strength for anchorage of a redirectional impact. However, during the full-scale test, the face of the box did not deform, so the two components did not interlock. Instead, the tabs in the W-beam bent over and the cable mechanism released at a relatively low load. As a result of this failure, the vehicle traveled through the system without being redirected. It was determined during this test that the face of the anchor box would not deform when loaded dynamicly, so a series of dynamic tests were performed to determine the effect that predeforming this face would have on the performance of the system. It was found that predeforming this face as shown in Figure 9 greatly enhanced the performance of this component of the system.

4.6 Test MCS-6 (4500 lb, 60 mph, 25 deg)

As a result of the dynamic testing performed on the cable attachment after Test MCS-5, the number of tabs was increased to 8, and the face of the cable attachment box was deformed for Test MCS-6, as shown in Figure 9. The number of tabs was increased by reducing the tab spacing but with no change in the length of the cable anchor box. Test MCS-6 was performed under the same conditions as test MCS-5, with a 1986 Ford LTD impacting the third post at 60 mph and 25 degrees. During this test, the cable anchor mechanism did not fail, but the soil conditions present, in conjunction with excessive foundation tube rotation, caused the posts to break off with little or no rotation. These problems may be attributed to a combination of weak posts, unexpectedly high compaction around the posts, and insufficient foundation tube lengths. Visual inspection of some of the broken posts indicated that they may have not met normal guardrail post quality standards. Soil compaction around the posts may have been artificially elevated by a sequence of compactions conducted as a result of rain delays of the testing. In addition, both foundation tubes moved in excess of 2¼ in. at the ground line.

4.7 Test MCS-7 (4500 lb, 60 mph, 25 deg)

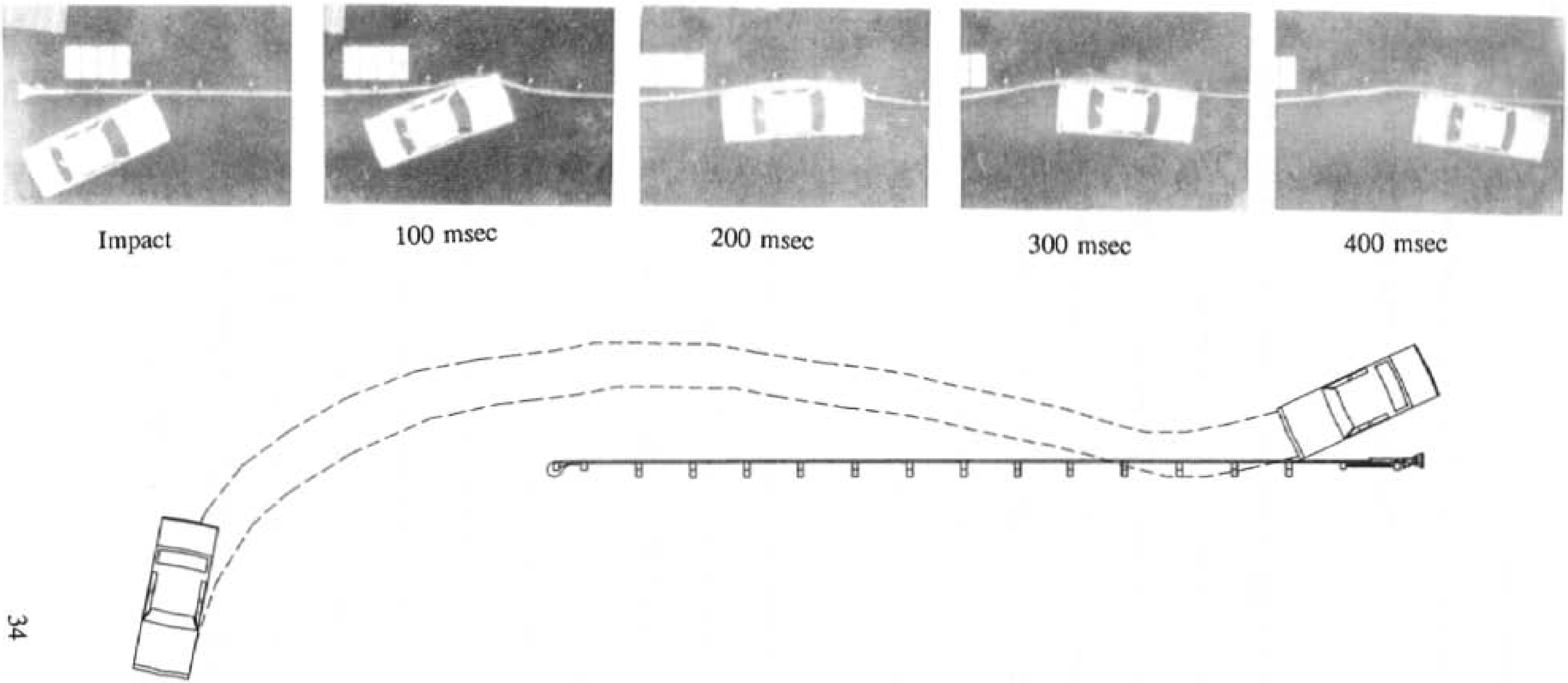
Several modifications were made to the system for Test MCS-7. During Test MCS-6, it was observed that the tabs in the cable breakaway mechanism were on the verge of failing. In order to provide a safety margin, the number of tabs and the length of the cable anchor box were increased from 8 to 10 tabs and approximately 20 3/4 to 25 11/16 in., respectively. The length of the foundation tubes were increased 6 in. to a total length of 6 ft - 6 in. to decrease the amount of deflection in these tubes during an impact. Guardrail posts used in this installation were inspected to assure reasonable quality. The soil compaction was also monitored to assure that there was not any excessive compaction situation encountered and conventional compaction procedures were used during installation.

The 1986 Ford LTD impacted the guardrail 14.5 in. upstream of post No. 3 at 60.0 mph and 26.2 deg. The vehicle was smoothly redirected and left the guardrail at an angle of 11.5 deg.

The analysis of the accelerometer data showed that the performance of the terminal passed the occupant risk criteria presented by NCHRP 230 (1), even though it is not required that this redirectional test meet this part of the criteria. The normalized longitudinal occupant impact velocity was 15.2 fps, well below the design limit of 30 fps. The maximum longitudinal ridedown acceleration of 1.4 g's was well below the design limit of 15 g's. The normalized lateral occupant impact velocity was 15.6 fps, which is below the design limit of 20 fps. The maximum lateral ridedown acceleration of 15.4 g's was just above the design value of 15 g's but well below the limit of 20 g's.

A summary of the test results is shown in Figure 24. The damage to the test vehicle is shown in Figure 25, and damage to the test installation is shown in Figure 26. Plots of the accelerometer data from Test MCS-7 can be found in Appendix A. A summary of the safety performance results is given in Table 1.

Note that the cable anchor box incorporated in the head-on impact testing (Tests MCS-3 and MCS-4) was approximately 5 in. shorter and had only 6 metal tabs. However, films of tests 3 and 4 indicate that the cable anchor box release mechanism performed very well and released from the guardrail well before striking the second post. Further, when the cable anchor mechanism was struck by a metal mallet, it was observed to rapidly release from the guardrail element. Therefore we believe that the revised cable anchor mechanism will perform adequately during head-on impact testing and does not need to be retested.



Test Number	MCS-7
Date	8/2/94
Installation	Metal Cutter Guardrail End Terminal
Length of Installation	100 ft.
Vehicle Model	1986 Ford LTD
Vehicle Weight	
Curb	3960 lbs
Test Inertial	4512 lbs
Gross Static	4512 lbs
Vehicle Impact Speed	60.0 mph
Vehicle Impact Angle	26.2 deg
Vehicle Exit Angle	11.5 deg

Vehicle Impact Location	14.5 in. upstream of Post No. 3
Occupant Impact Velocity	
Longitudinal	15.2 fps
Lateral	15.6 fps
Occupant Ridedown Accelerations	
Longitudinal	1.4 g
Lateral	15.4 g
Vehicle Damage Classification	
TAD	11-LFQ-3 11-LD-2
VDI	11LDES1

Figure 24. Summary of Test MCS-7

Figure 25. Test Vehicle Damage, Test MCS-7

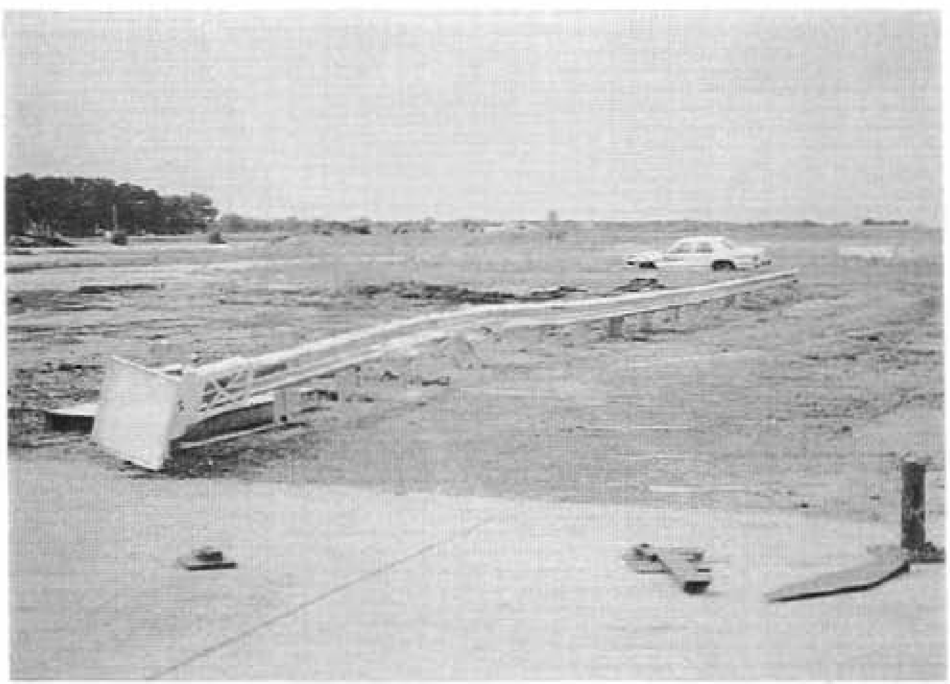


Figure 26. Installation Damage, Test MCS-7

Table 1. Performance Evaluation Results

Evaluation Factors		Evaluation Criteria	Test MCS-3	Test MCS-4	Test MCS-7
Structural Adequacy	A.	The test article shall smoothly redirect the vehicle; the vehicle shall not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.	NA	NA	S
	C.	Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.	S	S	NA
	D.	Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	S	S	S
Occupant Risk	E.	The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.	S	S	S
	F.	Longitudinal Occupant Impact Velocity (fps).	33.3	23.8	15.2
	F.	Long. Occupant Ridedown Decelerations (g).	17.3	9.2	1.4
Vehicle Trajectory	H.	After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.	S	S	S
	I.	In tests where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mph and the exit angle from the test article should be less than 60 percent of test impact angle, both measured at time of vehicle loss of contact with test device.	NA	NA	S
	J.	Vehicle trajectory behind the test article is acceptable.	S	S	NA

S Satisfactory
M Marginal
U Unsatisfactory
NA Not Applicable

5 CONCLUSIONS

Full-scale compliance testing of the metal cutting guardrail terminal showed that the system, with only minor revisions, passed all of the required criteria presented in NCHRP Report 230 (1) for an end treatment. It is believed that this system can be fabricated and marketed at a significantly reduced cost compared to other terminals of this type. By reducing this cost, a significantly larger number of these systems will be installed, and the overall safety of guardrail ends can be greatly improved.

6 REFERENCES

1. *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program Report No. 230, Transportation Research Board, Washington, D.C., March 1981.

7 APPENDIX A - ACCELEROMETER DATA ANALYSIS

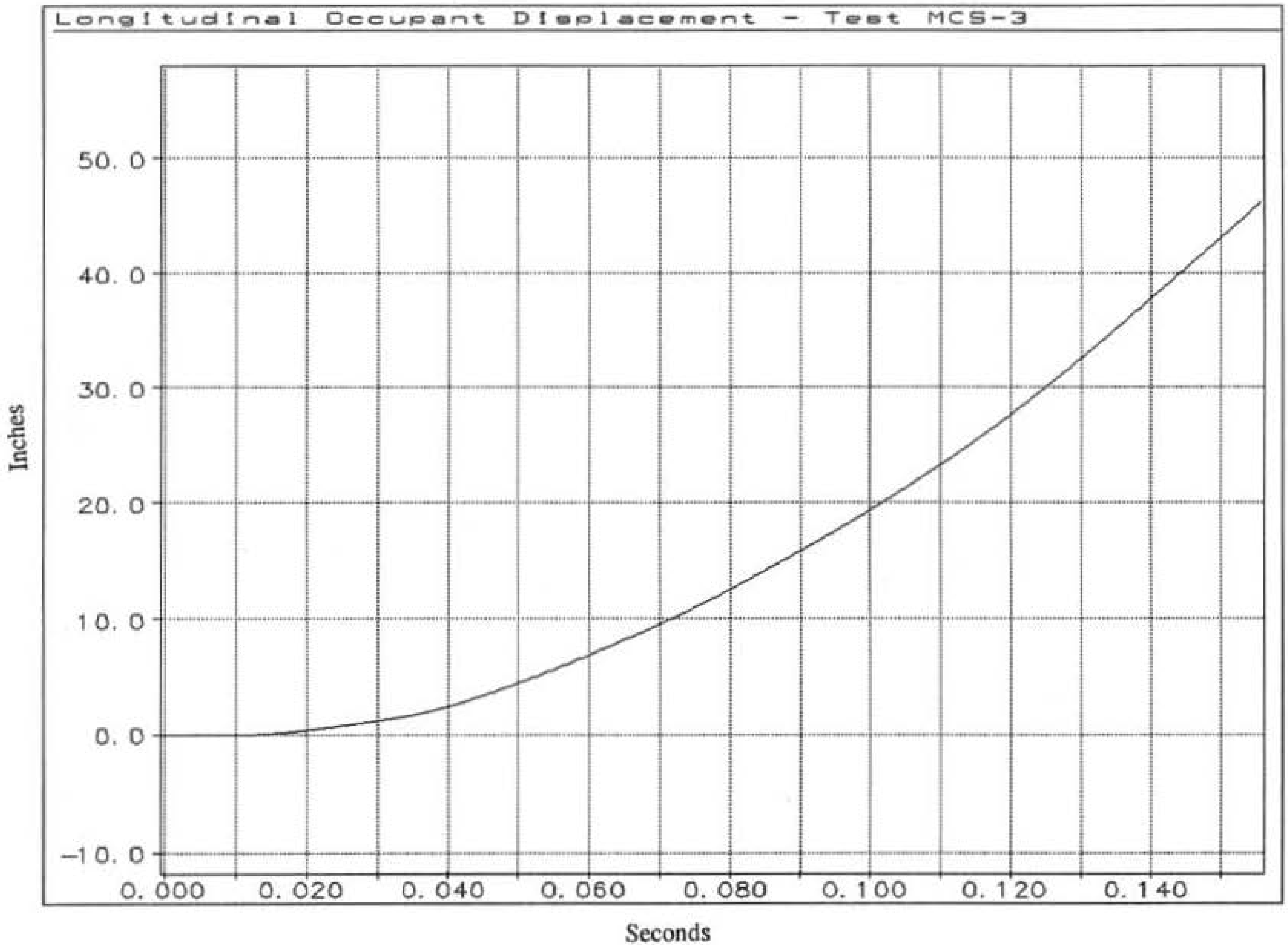


Figure A-1. Longitudinal Occupant Displacement, Test MCS-3

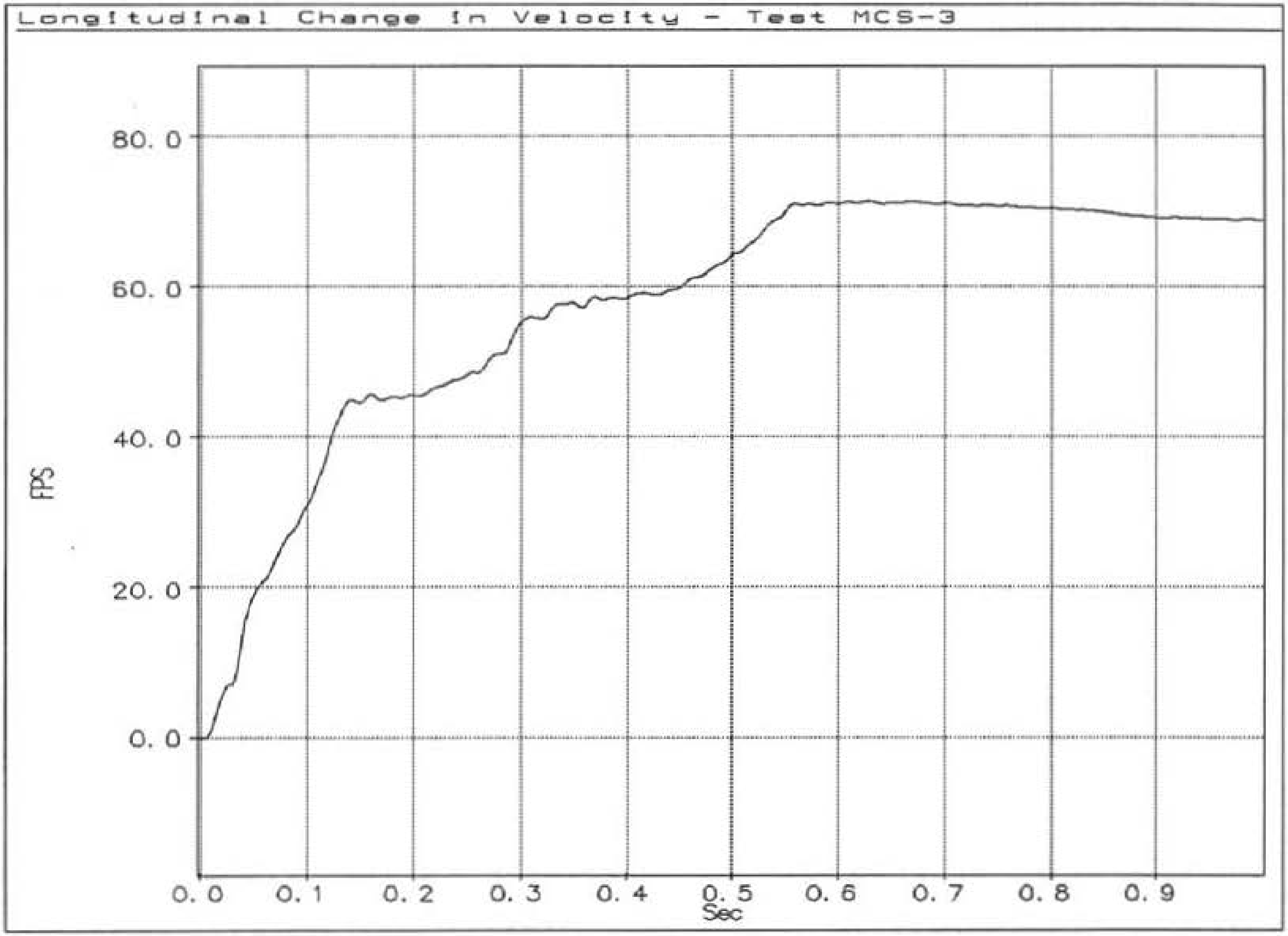


Figure A-2. Longitudinal Change in Velocity, Test MCS-3

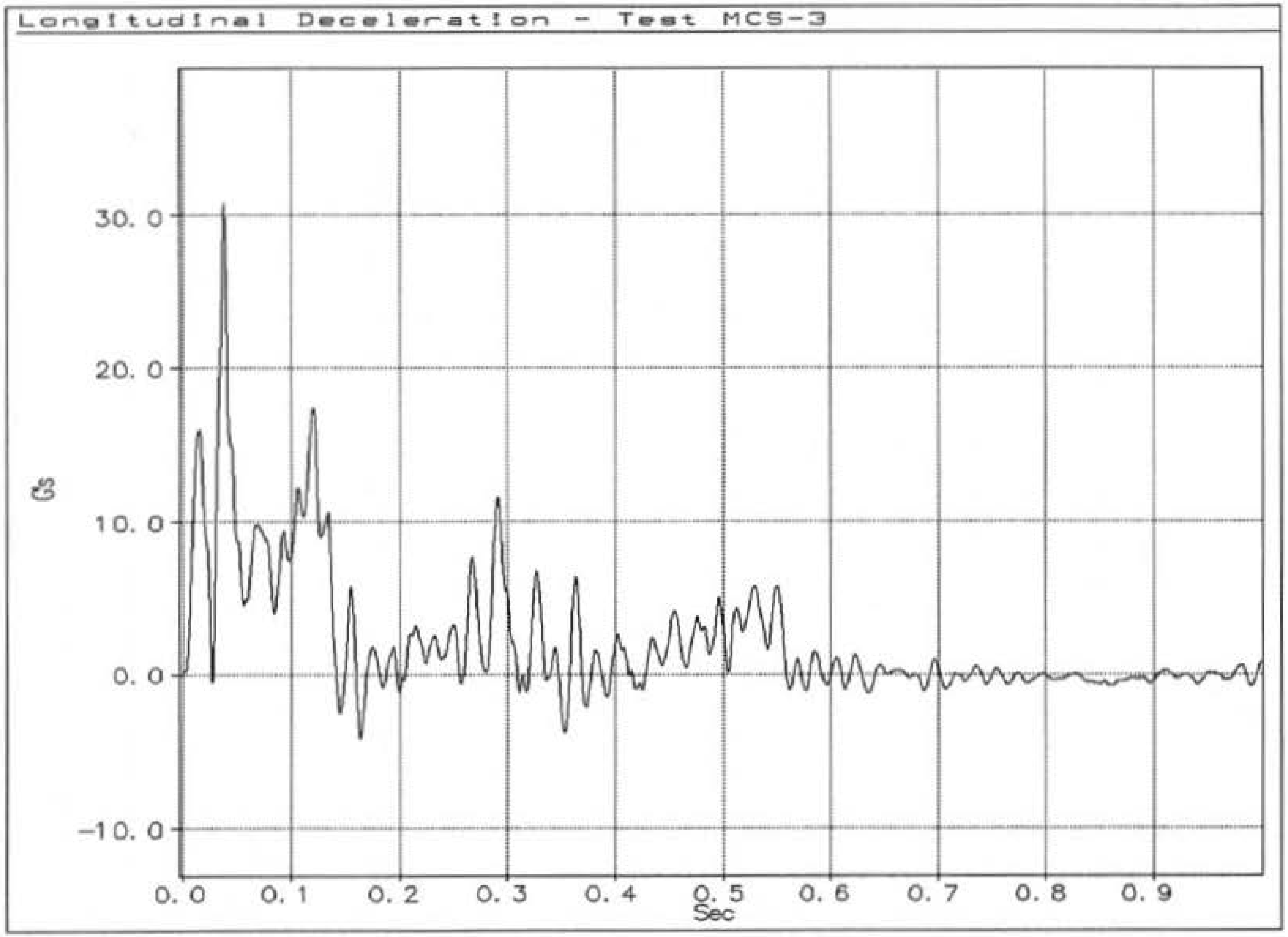


Figure A-3. Longitudinal Deceleration, Test MCS-3

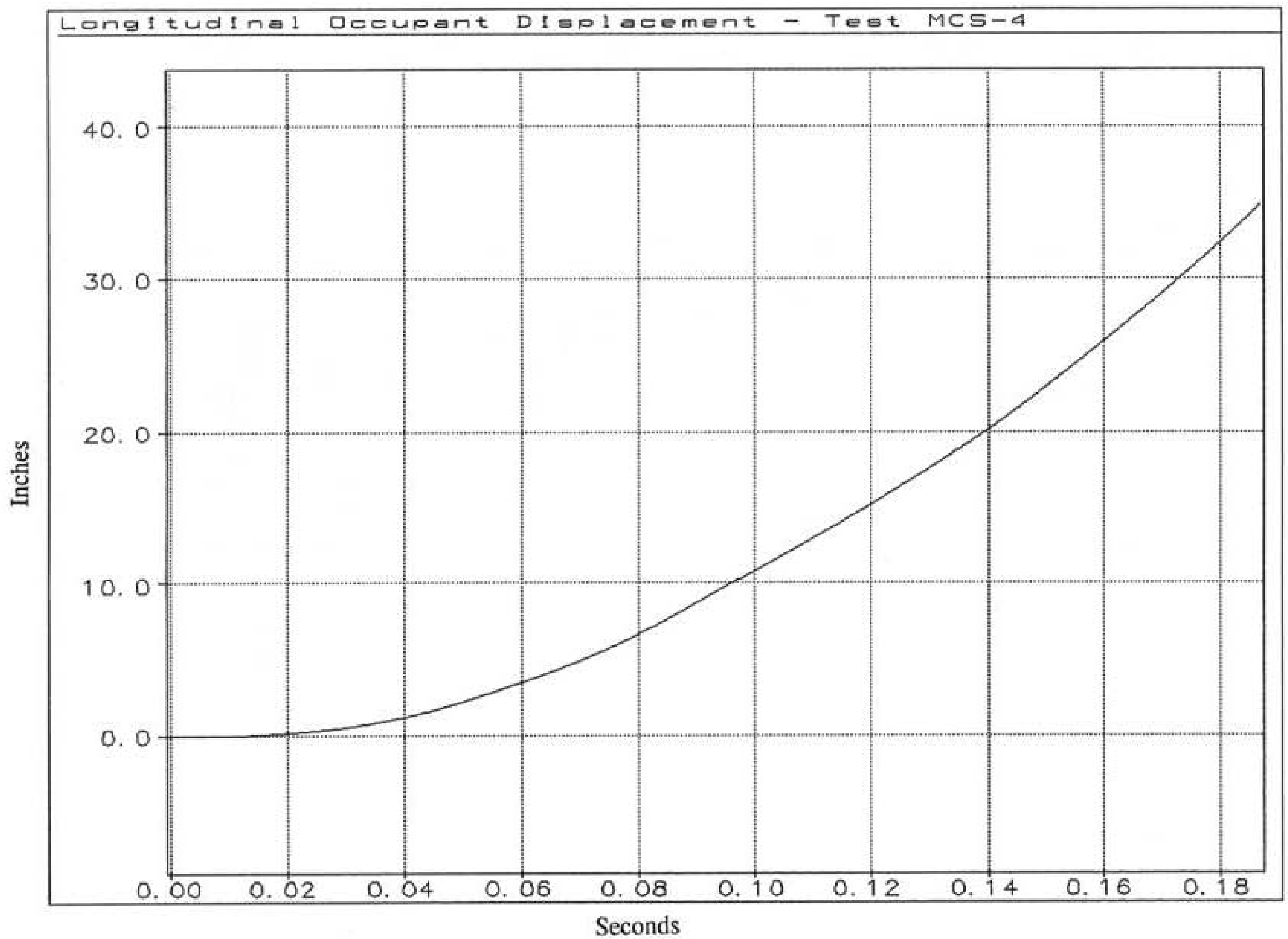


Figure A-4. Longitudinal Occupant Displacement, Test MCS-4

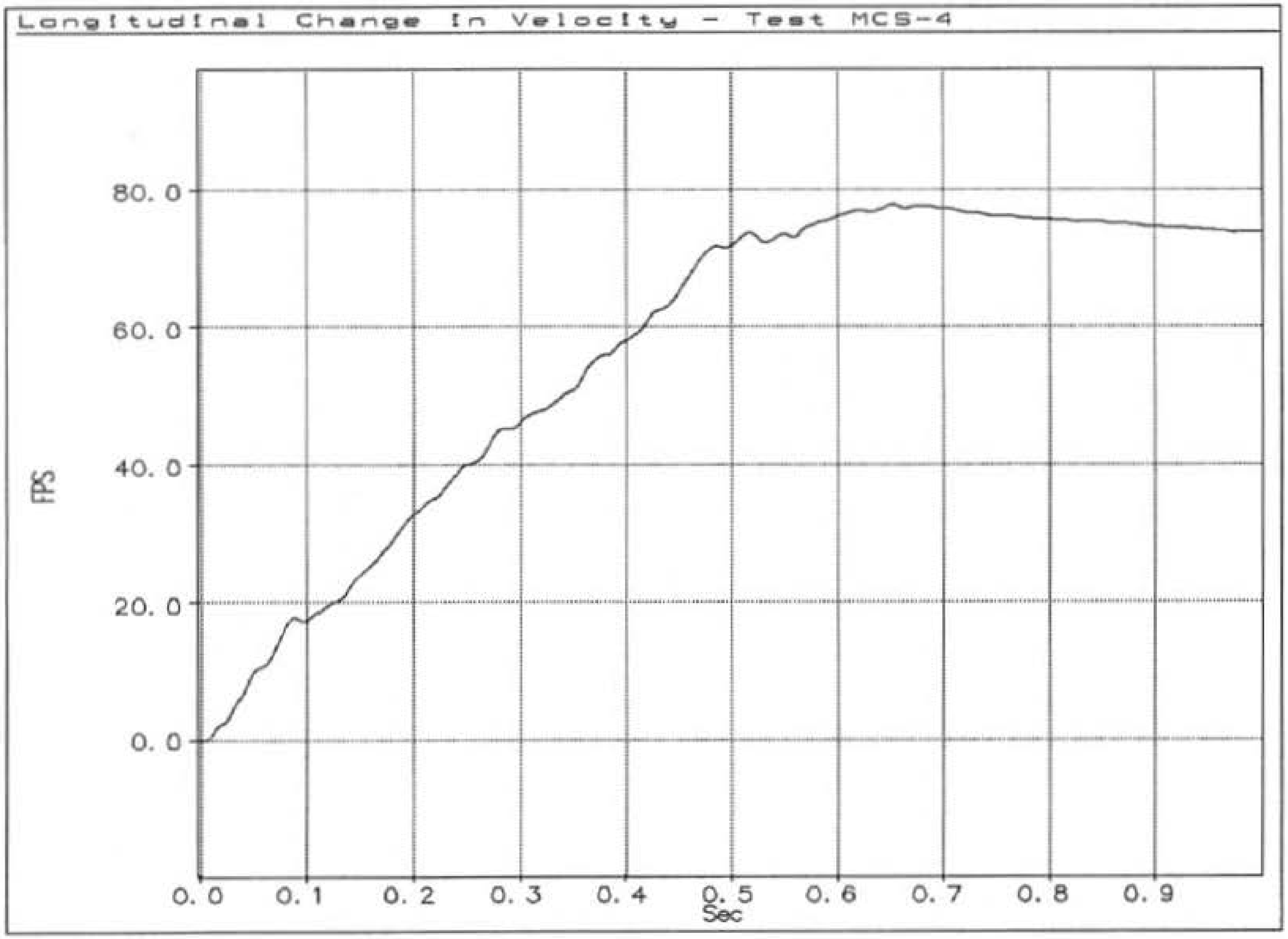


Figure A-5. Longitudinal Change in Velocity, Test MCS-4

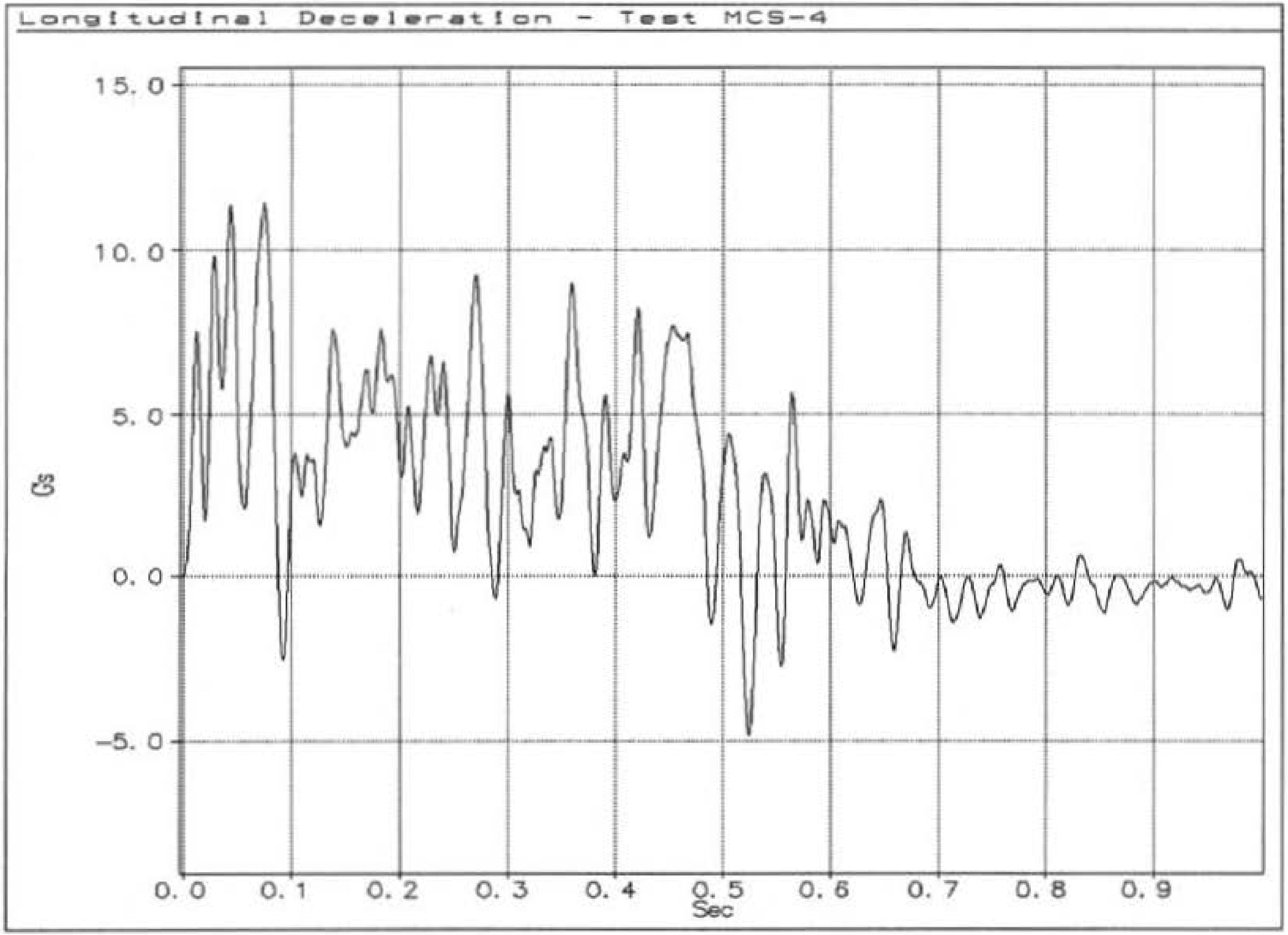


Figure A-6. Longitudinal Deceleration, Test MCS-4

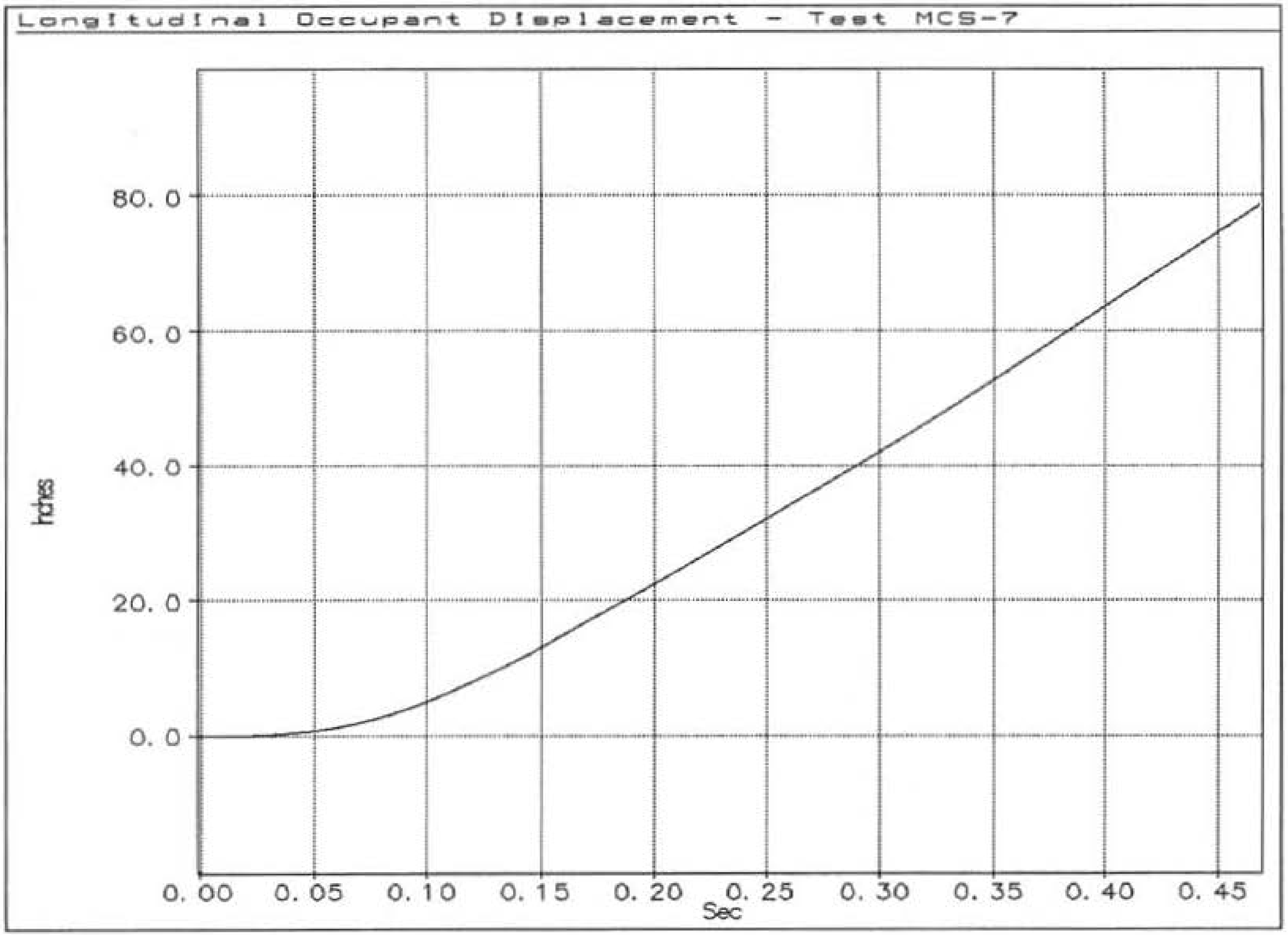


Figure A-7. Longitudinal Occupant Displacement, Test MCS-7

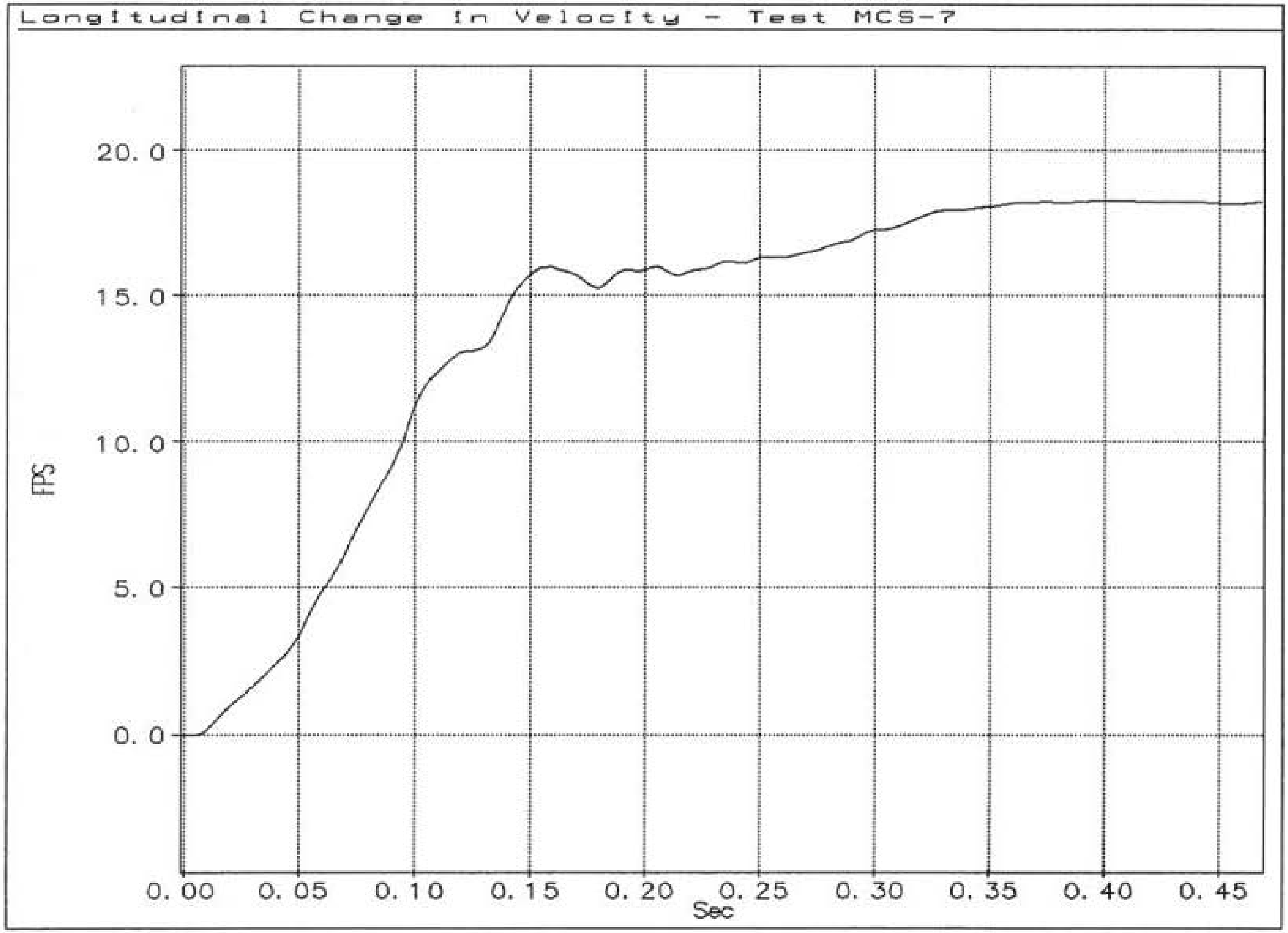


Figure A-8. Longitudinal Change in Velocity, Test MCS-7

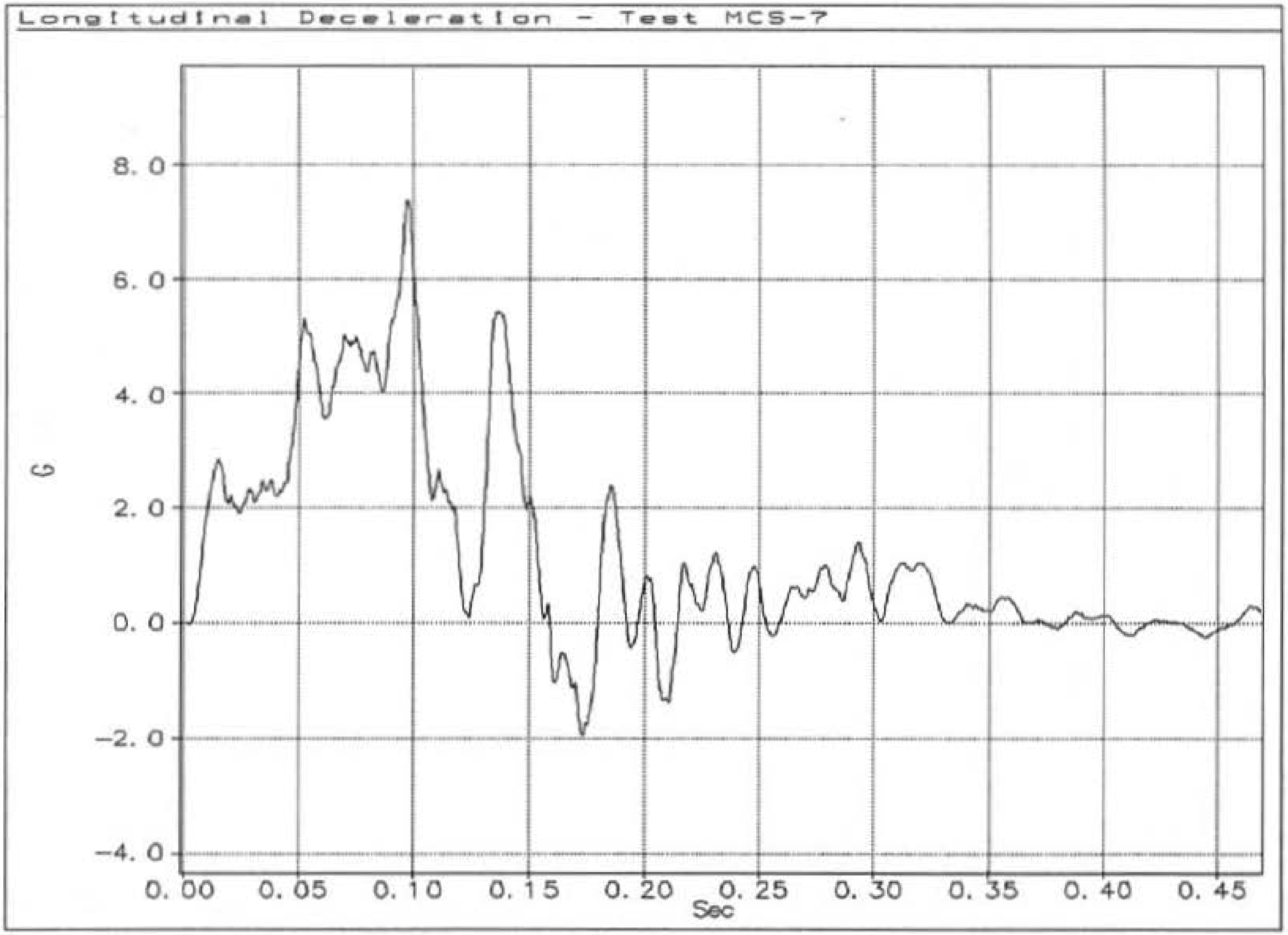


Figure A-9. Longitudinal Deceleration, Test MCS-7

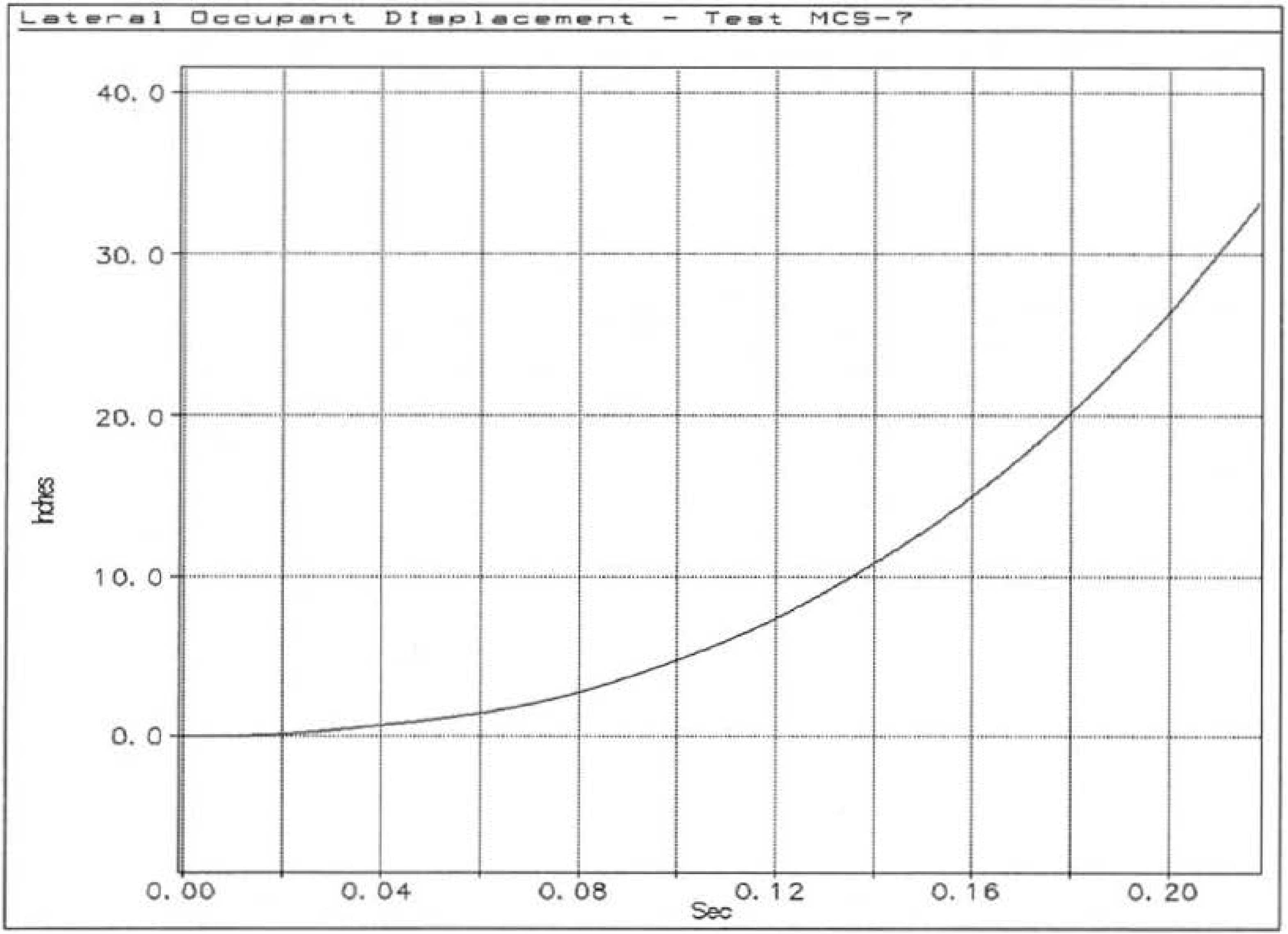


Figure A-10. Lateral Occupant Displacement, Test MCS-7

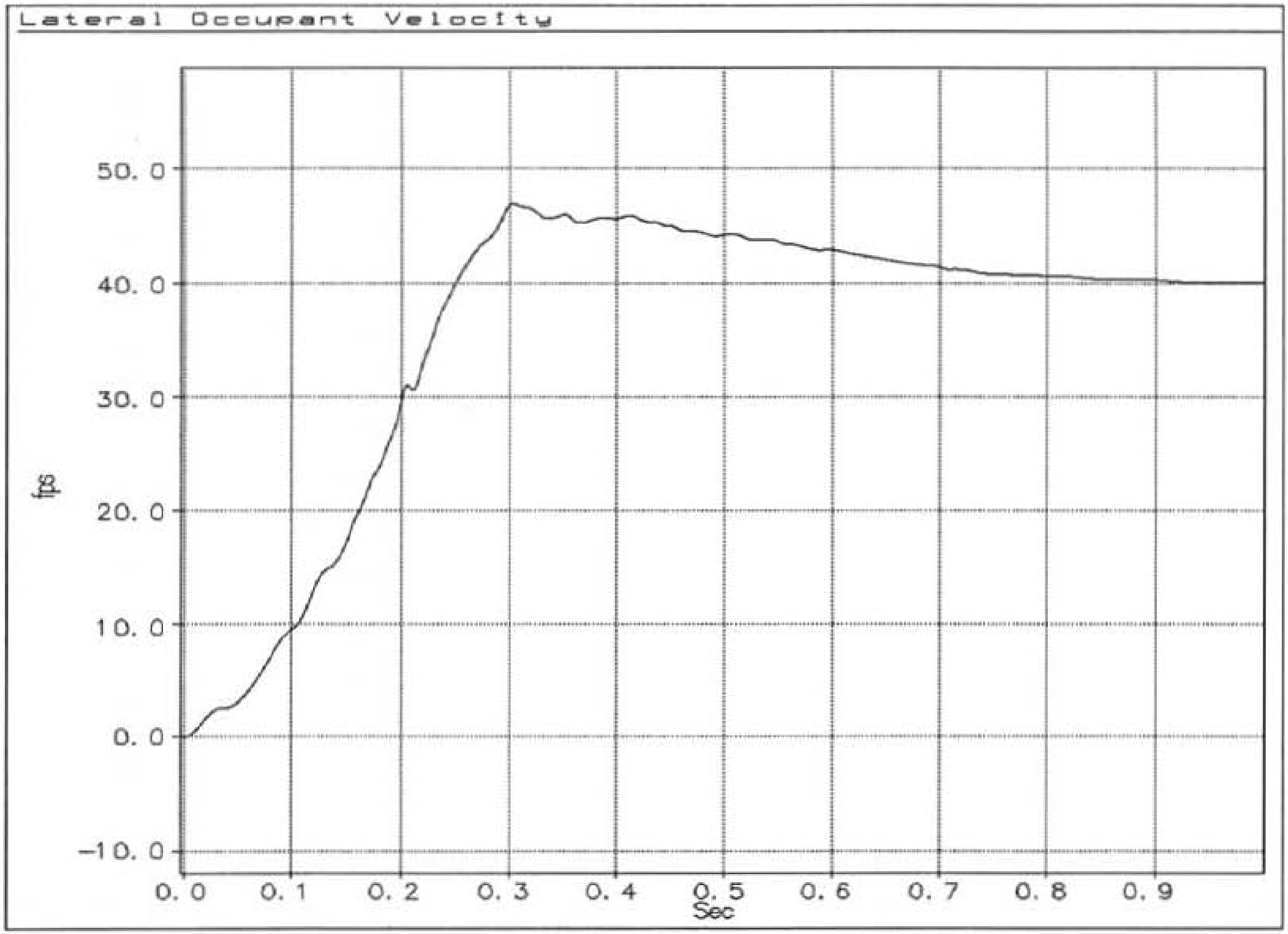


Figure A-11. Lateral Occupant Velocity, Test MCS-7

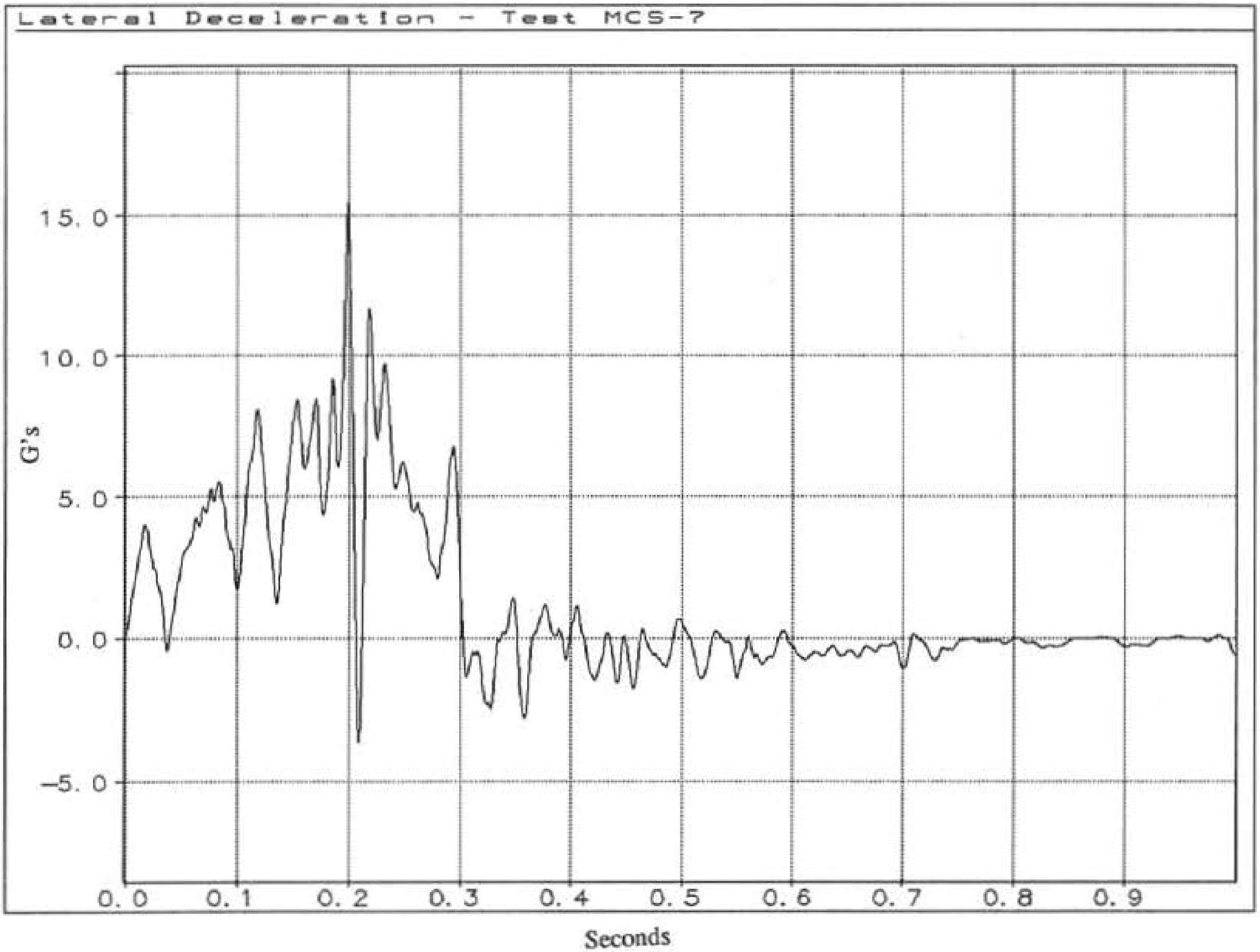


Figure A-12. Lateral Deceleration, Test MCS-7